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MDA Ice Detection and Measurement Camera Development and Validation for NASA-KSC (2004-2007)

Final Report

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Submitted to NASA as part of the NASA/TARDEC Space Act Agreement (SAA)

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Final Report

Executive Summary

1. Purpose and Development

The formation of frost, ice, and ice balls are common occurrences on the insulated External Tank (ET) of the Space Transportation System (STS) during National Aeronautics and Space Administration (NASA)-Kennedy Space Center (KSC), Florida launch preparations. The metal ET tank, 154 ft. tall and 27.5 ft. in diameter, is covered by insulating Sprayed On Foam Insulation (SOFI). However, internal ET fuel and oxidizer tanks contain large quantities of cryogens–in this case super cold liquid hydrogen (LH2) at minus 423°F and liquid oxygen (LO2) at minus 297°F. Complicating matters are Florida's humid and sometime cold weather that through condensation, support the formation of frost and ice. Although ice formation on the shuttle is more of a problem in the winter months, ice balls can form even in the hot summer months, because of cracks, voids, or other defects that may be present in the ET foam. Ice is a critical safety concern because of the possibility of it breaking off the ET at liftoff or during early vehicle assent. Falling ice could strike and possibly damage the Orbiter crew compartment windows, Reinforced Carbon-Carbon (RCC) panels on the leading edge of the Orbiter's wings, or its thermal protection tiles, thus placing the crew and vehicle at risk.

NASA's initial desires and requirements were that an ice detection and measurement system be developed for ET pre-launch inspections that would be capable of: a) differentiating ice from frost and water, b) be able to remotely detect and determine ice thickness to 1/16 in. thick (0.0625 in.), and c) be portable for on-pad use. The 1/16 in. thickness is a Launch Commit Criteria (LCC) limit for safe vehicle ascent. None of NASA's existing systems or visual observation methods met all of these requirements. Further, an underlying assumption for the use of any system was that undervalued ice thickness readings are the worst type of error for KSC operational personnel–that is, the system indicates that detected ice is thinner than it actually is–especially around the LCC.

Any developed system had to be transportable, fit in the pad elevator, and portable for use by the NASA ice and debris inspection team on launch pad access walkways and platforms at various structural levels during tanking tests and T-3 hour pre-launch inspections. Later, NASA identified a second LCC for hemispheric-shaped ice balls that can form on defective ET SOFI and fall off and strike the Orbiter. This LCC indicates a range of ice ball diameters that would be acceptable or not. But in general it was required that any system be able to detect ice balls of 2.3 in. in diameter or more at nominal T-3 hour inspection distances (i.e. 25 to 50 ft.). Finally, because of planned on-pad use, the system was required to meet launch complex safety requirements [e.g., be explosion proof and within electro magnetic interference (EMI)/electro magnetic compatibility (EMC) limits].

To help solve the above ice problems and challenges, which have existed since the earliest days of the STS Program starting with a first flight in 1982, a Space Act Agreement (SAA) was signed on January 21, 2004 between James Kennedy the NASA-KSC Center Director, and Dr. Richard McClelland the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC) Director.[1] This SAA opened that door for the exploration of future mutually beneficial organizational activities between the agencies. The initial project was the development of a system

for remote ice detection and measurement to be accomplished under the terms of a Statement of Work (SOW) entitled: "Ice/Frost Detection and Evaluation." Ronald Phelps of NASA-KSC's Shuttle Processing Business Office, and Dr. Thomas Meitzler of TARDEC's Visual Perception Lab (VPL) jointly signed this SOW in March 2004, and renewed it in January/February 2006.[2] Under the SAA and SOW, members of TARDEC's VPL performed a technology search and evaluation of potential electro-optical systems capable of remotely detecting the presence and determining the thickness of ice. The initial search included a number of potential technologies including radar, surface acoustic waves, and ultrasound. Research by VPL investigators indicated that it might be possible to detect and image ice-covered areas using an infrared (IR) camera system.

In addition to performing technology reviews, TARDEC's VPL was to serve as an independent testing and evaluation organization, taking advantage of seasonal cold weather available for testing in the Michigan area where TARDEC is located. Later, they also accepted the responsibility of being the procurement and contracting agent using NASA provided funds. In this way, TARDEC would have control of all aspects of system acquisition, testing, and independent evaluation. NASA would remain the requirements advisor and ultimate customer for needed system capabilities, and would provide advice and any additional funding needed for the development of a remote ice detection and measurement system capability. But in the end, the goal and plan was that a three-way, active partnership would be developed and maintained between NASA, TARDEC, and whoever supplied the needed system.

The development and validation of a prototype ice detection and measurement system occurred over a three-and-a-half year period from the signing of a SAA on January 21, 2004, until the system was used by the NASA-KSC ice and debris team during T-3 hour inspections for STS-116, STS-117, and STS-118 prior to their successful December 9, 2006, June 8, 2007, and August 8, 2007 launches, respectively. The initial and ultimate objectives of this joint research effort were to identify, investigate, and test conceptual or commercially-available sensors that had the potential to remotely detect and quantitatively measure ice formed during pre-launch operations on the insulating SOFI of the Space Shuttle's ET. Project milestones and activities that began with the signing of the 2004 SAA eventually led to the system's readiness and use to support the August 2007 launch of STS-118. However, no significant ET SOFI surface ice or hemispheric-shaped ice balls were present during the latter summer launch period when ambient temperatures exceed 95°F during launch day inspections.

2. Methods Used and Activities

This report traces the development of a capability for an STS ice detection and measurement system for use during pre-launch inspections to evaluate flight safety. Several key milestones were important in the evolution of the development of a remote system for NASA's pre-launch inspection use. In 2004, and following the signing of a joint SAA and SOW, investigation began by TARDEC of several ice detection and measurement technologies–two conceptual and one commercial. After testing and evaluation of two available systems that were still in conceptual development, TARDEC recommended to NASA that the concept and system developed by MacDonald, Dettwiler and Associates Ltd. (MDA–formally known as MDR) of Brampton, Ontario, Canada showed the greatest potential for meeting NASA's needs and requirements.[3] The MDA ice detection system operates on the physical principle discovered by the inventor, Dr. Dennis Gregoris, that there is a specific wavelength band over which the electromagnetic (EM) reflectance spectra of ice and water are significantly different.[4,5] These bands are part of what is usually referred to as the near IR or short wave infrared (SWIR) portion of the EM spectrum, between 1.1 and 1.4 microns.

An advantage of working with this company was that it is well known to NASA for space-borne robotic arms and systems such as Canadarm that is used in the Space Shuttle payload bay, and the International Space Station's Canadarm2, Mobile Base System, and the Special Purpose Dexterous Manipulator. The first joint meeting between NASA, TARDEC, and MDA occurred on August 5, 2004 at KSC with discussion and tours to: a) better understand KSC's ice detection and measurement system requirements, b) provide a better understanding of the KSC pre-launch operational environment, and c) determine the "way ahead."

In late 2004, a NASA-funded TARDEC contract to MDA was approved, and in early 2005 a proof-of-concept system was delivered and tested in TARDEC facilities in Warren, Michigan. During the 2005 start of year winter period, various concept system operating features and capabilities were tested.[6] Initially important was the determination that the MDA system (hereafter referred to as the ice camera) could differentiate between ice, thin frost, and water. Also evaluated was the system's effectiveness in accurately estimating the thickness of acreage ice on small ET SOFI test samples provided by NASA. During the year, and driven by the analysis of test data, additional funding was provided by NASA, and TARDEC contracted with MDA to make needed system improvements.

In early 2006, testing of a prototype (and later improved) system began. Instead of using TARDEC facilities in Warren, testing was moved to better facilities at nearby Selfridge Air National Guard Base (SANGB) in Harrison Township, Michigan (hereafter referred in this report as Selfridge). This facility was selected because it offered more advantages over any test area available at TARDEC in terms of test distances, environmental control, and overall operating space. During testing the system was found to be able to differentiate between ice and water, however, it had some instability in: a) ice thickness readings, b) was not linear over test distances, and c) underestimated ice/frost thickness.[7] During this test period, ice camera performance in remote ice thickness accuracy improved through recalibration based on changes in test design, followed by repeated test data collection and analysis, followed by recursive software modification by Dr. Dennis Gregoris of MDA. But the MDA system still had not achieved a desired level of ice thickness accuracy. Regardless, this system was considered by NASA as a breakthrough in remote ice detection and measurement,[7] and was successfully used during a T-3 hour inspection and detected and recorded ET SOFI ice during the December 2006 launch of STS-116.

In 2007, additional testing was accomplished at Selfridge and the system was again recalibrated by MDA based on acquired and analyzed test data. Several software recalibrations eventually proved to be successful in increasing system accuracy to the level needed to meet NASA operational and decision making LCC needs. Also, during 2007 thick shell and thin shell ice ball detection tests were successfully performed and data obtained. This prototype version of the ice camera was found to be in calibration and was validated at Selfridge at the conclusion of testing. Shortly thereafter it was shipped to NASA-KSC for T-3 hour inspection pre-launch support for STS-117. Following post-shipment testing at KSC, the system was again verified as being in calibration, and was collectively felt by NASA, TARDEC, and MDA representatives to be operationally ready. No ET SOFI acreage ice and only two *frost* ice balls were reported during the T-3 hour inspection by the ice team members for the June launch. Unfortunately, the ice camera was not working to full capacity due to a videocassette recorder (VCR) tape jam, and no data were recorded. The ice camera was sent to MDA-Canada for repair and returned to KSC for use during STS-118 T-3 hour inspections. There were no significant problems with the system during this mission, and the tape system worked to collect data. However, because of the high temperatures during the August 8, 2007 inspections, no acreage ice or ice balls were visually observed or

detected by the system. However, an ice build up was observed on the O2 feed line bracket and on a flange near the bottom of the ET, which is not unusual,

3. Conclusions and Recommendation

The primary conclusions reached as a result of the evolution and development of the prototype MDA ice detection and measurement system are that: a) the concept has been proven feasible, b) the system can be calibrated for KSC operational ice inspections, and c) the system is significantly better than any other visual inspection or instrumentation available to NASA to determine if ET acreage ice and ice ball LCCs have been exceeded. It should be realized that the present system remains an experimentally calibrated tool and prototype, which was not designed or constructed to be a ruggedized, reliable, or operational unit. Regardless, extensive testing of the system has determined the MDA ice camera has the following capabilities and limitations:

Ice/frost detection–It was found early (2005) that the system cannot differentiate between ice and frost. During testing it was found that frost (defined by NASA as ice having a density of 18 lb/ft^3 or less), even when packed and having some thickness, appears much thinner than it actually is. If thick enough, frost appears to be low density ice. The ice camera cannot accurately measure ice under frost. But from a system requirement or operational reality, frost was is not an STS problem or LCC consideration because it does not form with any thickness that is a launch constraint. A problem occurs when frost densifies into ice as a function of time, temperature, and relative humidity.

Ice/water differentiation–Early testing (2004 and 2005) proved conclusively that the ice camera could clearly differentiate between clear water and clear ice. Water is displayed as black and ice as a color in the ice camera display. This is a significant capability, because to the human eye even at short distances, water and clear ice are very similar and almost impossible to distinguish between. Water, in the form of condensate, is not a pre-launch constraint on SOFI, unless it freezes and exceeds the 0.0625 in. LCC thickness. Fortunately, the MDA ice camera is an ice detection system that clearly differentiates ice from water.

Acreage ice thickness measurement–Accurate ice thickness determination for SOFI acreage ice was the most difficult ice camera capability to develop. Several years (2005, 2006, and 2007) and recursive cycles of ice formation, data collection, recalibration, retesting, data collection, and recalibration were required to achieve this goal. When agreement was reached to limit viewing distances and angles to reasonable and nominal KSC operational limits, a successful calibration was achieved that improved system accuracy to an acceptable level. These limits were a viewing angle of 80-90 degrees, viewing distances from 25 to 50 ft., and for ice thickness up to and slightly higher than the LCC ice thickness of 0.0625 in. Also, ice densities, which the MDA is sensitive to, were limited for the purpose of system calibration, to nominal KSC ice densities of 30 to 40 lb/ft^3 (normalized to 35 lb/ft^3). Under these reasonable and nominal viewing angle and distances, the ice camera had been proven to be accurate, and more importantly it does not underestimate ice thickness, i.e. indicate ice that is thinner than it actually is–the worst type of error for NASA.

Ice ball detection and measurement–An LCC for thick and thin-shelled ice balls was evolving at the start of this SAA/SOW project, and was identified to TARDEC and MDA during the 2006 testing period. Thick ice balls were identified as hemispheres having a wall thickness of 0.40 in. with a frost center. Thin shell ice balls have a wall thickness of 1/8 to 1/10 in. maximum with a frost center and a donut-shaped base. Testing of both types of balls was accomplished in 2007 with good results, but a limited understanding of the capability of the ice camera to determine ice shell

thickness presently exists. From thick and thin shell ice ball test results, it is known that three inch diameter ice balls are visible from 25 to 60 ft. at most test viewing angles (i.e. 90, 45, and 20 degrees), two inch diameter ice balls are visible between 25 and 40 ft. for most test viewing angles, and one inch diameter ice balls are not visible beyond 25 feet. Based on LCC concern for ice balls larger than 2.3 in., the ice camera should not have a problem detecting ice balls of concern on SOFI at a range of distances of 25 to about 50 ft. What is not understood yet is the capability of the system to measure ice ball shell and content thickness. Complicating the matter is the fact that some ice balls are donut shaped at their interface with SOFI that they are attached to and grow from.

Portability–Except for the weight and maneuverability problem, NASA is generally satisfied with the ice camera for movement to and around launch pad access walkways and platforms. But the bulky nature of the present design and weight of more than 200 lbs. makes the system awkward to maneuver. The basics components that determine the weight and size of the ice camera design for operation are a battery, purged enclosures, a gaseous nitrogen purge bottle, and an operator display and data recording system. With the replacement of the VCR with a more reliable digital video recorder (DVR), some few pounds will be saved. The design of the operational system size and weight will ensure it is lighter and more user-friendly.

The following table summarizes the operational performance capabilities of the prototype MDA ice camera system that have been achieved from reiterative development testing at TARDEC, Selfridge, and KSC, and field human factor studies and operational use during three KSC STS pre-launch inspections of acreage ice and bracket and vent ice when it existed. The term measurement is used here to indicate the reading displayed on the ice camera operator panel.

Operational Parameters	Capabilities
Operational viewing range	25 to 50 ft. (with some detection of ice at 100 ft.) Note: the system should not be used within 25 ft. of the vehicle.
Illumination	Full sunlight to total darkness
Ice thickness measurement range	0.020 in. to 0.250 in.
Calibrated measurement range	0.020 in. to 0.080 in.
Accuracy of readings within calibrated measurement range	±0.010 in.
Ice detection viewing angles (from normal to the SOFI surface)	90 to 20 degrees
Operational ice measurement viewing angle limits	90 to 65 degrees
Ice ball detection (thick and thin) within the operational viewing range and viewing angles	Three in. diameter balls between 25ft. and 50 ft from angles of 90 to 20 degrees. Two in. diameter balls between 25 and 40 ft. from most viewing angles. One in. balls not visible beyond 25 ft.
Ice under frost	Reduced ice thickness reading under very thin frost (0.010 in.), and no reading with frost > 1/4 in.
Eye protection	Operators should not look directly

	into the flashing strobe
Operational system use time	> 2 hours
System weight	Approx. 200 lb.

Several recommendations are advanced for consideration. First, based on what has been learned to date, that a new round of testing be initiated by TARDEC/NASA at Selfridge when the ice camera is available between STS launches. The focus of this investigation would be on improving thicker ice measurement accuracy above the LCC of 0.0625 in. for nominal density ice, and more extensive ice ball testing to expand shell thickness evaluations and content measurement understanding. It would be advantageous if this testing occurred prior to the planned December 2007 launch of STS-120 when ice balls have a potential for forming on ET SOFI in the cold Florida "winter" air. There may also be a test methodology justification for using liquid helium as the cryogen to assist in the formation of test ice balls, as was used during earlier NASA Stennis Space Center testing to develop an ice ball LCC. If possible it is better to test at Selfridge during the colder winter period (November through April) when ice density is easier to control, and ice forms more quickly for ice ball attachment. It is also suggested that in the future, an enclosure around the test SOFI and Dewar (8 ft. x 10 ft. or greater) should be constructed with air conditioning to help control and maintain ice thickness and density within the Selfridge hangar and KSC test facility.

Second, as changes are made to the existing MDA prototype system to improve its functionality, reliability, and accuracy, more extensive testing and calibration verification at Selfridge may be needed for future NASA-KSC launch processing inspections. It is now recognized that the present system, which has evolved from a concept model made from off-the-shelf components, lacked the reliability needed during extended testing and KSC operational transportation and use during pre-launch inspections. Additional Selfridge testing to verify the system's functionality, reliability, and accuracy would not be a wasted effort, because it is planned that the present ice camera will serve as a backup system for KSC inspections even after a replacement and next-generation operational system is available–perhaps not for more than one year. But not all testing would occur at Selfridge. The more frequently the system is used at KSC for in-field mobility/human factor/engineering testing and operational use, the more data can be collected for analysis, and the sooner improvements to the present system can be made. Also, data and analysis from any testing at Selfridge and field evaluations at KSC would greatly benefit the design and development of an operational system.

Third, consideration should be made by NASA to make available dedicated land lines on launch pad structures (i.e. FSS and RSS) for ice camera connections at various selected levels. For inspections, the ice camera could then be connected at various points on the structures for data distribution to and display in the LCC "Ice Castle." This data redistribution, would serve to aid the real-time decision making process for ET SOFI acreage ice and ice ball LCC violation determination. In addition, data recording in the LCC would serve as a backup to internally recorded ice camera data. However, to make these displays and recordings possible, the ice camera would have to be modified by MDA to put a cable output on the camera that is compatible with data cable connectors on the launch pad structures.

Finally, NASA should fund as soon as possible, and participate with TARDEC and MDA, in the design, development, and testing of an operational ice detection and measurement system that is customized for KSC STS ET acreage ice, ice ball, and ice formations on brackets, vents, and other cold surfaces. The sooner new funding is made available the better, because it is estimated that an

operational system will require twelve months for development, construction, and verification testing. In the meantime during Florida's winter launch periods, the present prototype and eventual operational system should be invaluable for remaining STS flights in detecting and accurately determining the presence and thickness of ice on ET SOFI and the presence of ice balls. Also, there is every reason to believe that any developed ice camera would be useful for checking ice formations on cryogen loaded NASA or military vehicle stages or tanks, and for future NASA Crew Exploration Vehicle (CEV) systems being designed with SOFI for cryogenic tank insulation planned for launch as early as 2014.

> The best encouragement and endorsement of this development effort has been Charles Stevenson of NASA's statement, after he reviewed recent Selfridge test data, that: "The SAA team has developed an ice detection and measurement system in less than three years, that has the potential to solve a problem that NASA has struggled with for more than 25 years–SOFI acreage ice detection and measurement, and more recently ice ball detection." Both problems have important LCC implications for future launches.

MDA Ice Detection and Measurement Camera Development and Validation for NASA-KSC

Final Report

A. Introduction and Background

1. Project Importance and Requirements

The formation of frost, ice, and ice balls are common occurrences on the insulated External Tank (ET) of the Space Transportation System (STS) during National Aeronautics and Space Administration (NASA)-Kennedy Space Center (KSC), Florida launch preparations. The metal ET tank, 154 ft. tall and 27.5 ft. in diameter, is covered by insulating Sprayed On Foam Insulation (SOFI). However, internal ET fuel and oxidizer tanks contain large quantities of cryogens–in this case super cold liquid hydrogen (LH2) at minus 423°F and liquid oxygen (LO2) at minus 297°F. Complicating matters are Florida's humid and sometime cold weather that through condensation, support the formation of frost and ice. Although ice formation on the shuttle is more of a problem in the winter months, ice balls can form even in the hot summer months, because of cracks, voids, or other defects that may be present in the ET foam. Ice is a critical safety concern because of the possibility of it breaking off the ET at liftoff or during early vehicle assent. Falling ice could strike and possibly damage the Orbiter crew compartment windows, Reinforced Carbon-Carbon (RCC) panels on the leading edge of the Orbiter's wings, or its thermal protection tiles, thus placing the crew and vehicle at risk.

Figure 1. Ice/frost formed on an ET

NASA's initial desires and requirements were that an ice detection and measurement system be developed for ET pre-launch inspections that would be capable of: a) differentiating ice from thin frost and water, b) be able to remotely detect and determine ice thickness to 1/16 in. thick (0.0625 in.), and c) be portable. The 1/16 in. thickness is a Launch Commit Criteria (LCC) limit for safe vehicle ascent. None of NASA's existing systems or visual observation methods met all of these requirements. Further, an underlying assumption for the use of any system was that undervalued ice thickness readings are the worst type of error for NASA operations personnel–that is, the system indicates that detected ice is thinner than it actually is–especially around the LCC.

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of 2.3 in. in diameter or more at nominal T-3 hour inspection distances (i.e. 25 to 50 ft.). Finally, because of planned on-pad use at various inspection levels on the structure, the system was required to meet launch complex safety requirements (e.g., be explosion proof and within EMI/EMC limits).

Project team lessons learned and some open issues are identified in Appendix 14. Abbreviations used in this report and references are contained in Appendices 15 and 16, respectively.

2. SAA/SOW

To help solve the above challenges, which have existed since the earliest days of the STS Program starting with a first flight in 1982, a Space Act Agreement (SAA) was signed on January 21, 2004 between James Kennedy the NASA-KSC Center Director, and Dr. Richard McClelland the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC) Director.[1] This SAA opened that door for the exploration of future mutually beneficial organizational activities between the agencies. The initial project was the development of a system for remote ice detection and measurement to be accomplished under the terms of a Statement of Work (SOW) entitled: "Ice/Frost Detection and Evaluation." Ronald Phelps of NASA-KSC's Shuttle Processing Business Office, and Dr. Thomas Meitzler of TARDEC's Visual Perception Lab (VPL) jointly signed this SOW in March 2004, and renewed in January/February 2006.[2] Under the SAA and SOW, members of TARDEC's VPL performed a technology search and evaluation of potential electro-optical systems capable of remotely detecting the presence and determining the thickness of ice. Under the SAA and SOW, members of TARDEC's VPL performed a technology search and evaluation of potential electro-optical systems capable of remotely detecting the presence and determining the thickness of ice. The initial search included all technologies, i.e. radar, surface acoustic wave, ultrasonic. Research by VPL investigators indicated that it might be possible to detect and image ice-covered areas using an infrared (IR) camera system.

In addition to performing technology reviews, TARDEC's was to serve as an independent testing and evaluation organization, taking advantage of seasonal cold weather available for testing in the Warren (Detroit), Michigan area where TARDEC is located. Later, they also accepted the responsibility of being the procurement and contracting agent using NASA provided funds. In this way, TARDEC would have control of all aspects of system acquisition, testing, and independent evaluation. NASA would remain the requirements advisor and ultimate customer for needed system capabilities, and would provide advice and any additional funding needed for the development of a remote ice detection and measurement system capability. But in the end, the goal and plan was that a three-way, active partnership would be developed and maintained between NASA, TARDEC, and whoever supplied the needed system.

3. TARDEC/NASA Investigation and Testing Milestones

The development and validation of a prototype ice detection and measurement system occurred over a three-and-a-half year period from the signing of a SAA on January 21, 2004, until the system was used successfully by the NASA-KSC ice and debris team during T-3 hour inspections for STS-118 prior to its successful August 8, 2007 launch. The initial and ultimate objectives of this joint research effort were to identify, investigate, and test commercially available techniques, and sensors that have the potential to remotely detect and quantitatively measure ice formed during pre-launch operations on the insulating SOFI on the Space Shuttle's ET. Table 1 that follows lists the dates and key milestones that began with the signing of a SAA and eventually led to the system's readiness and use to support the launch of STS-117 and post-launch system inspection. During Florida's winter launch periods, the system will be invaluable for remaining STS flights in detecting and

accurately determining the presence and thickness of ice on ET SOFI and the presence of ice balls. There is no reason to believe that any ice detection and measurement system developed would not be useful for present and planned future NASA and military cryogenic launch vehicle stages with SOFI for tank insulation.

Several key milestones were important in the evolution of the development of a remote system for NASA's pre-launch inspection use. In 2004, and following the signing of a joint SAA and SOW, investigation by TARDEC of several ice detection and measurement technologies began. After testing and evaluation of three systems, two conceptual and one commercial, TARDEC recommended to NASA that a conceptual system developed by MacDonald, Dettwiler and Associates Ltd. (MDA–formally known as MDR) of Brampton, Ontario, Canada showed the greatest potential for meeting NASA's needs and requirements.[3] The MDA ice detection system (hereafter referred to as the ice camera) operates on the physical principle discovered by the inventor, Dr. Dennis Gregoris, that there is a specific wavelength band over which the electromagnetic (EM) reflectance spectra of ice and water are significantly different.[4,5] These bands are part of what is usually referred to as the near IR or short wave infrared (SWIR) portion of the EM spectrum, between 1.1 and 1.4 microns.

An advantage of working with this company is that it is well known to NASA for space-borne robotic arms and systems such as Canadarm that is used in the Space Shuttle payload bay, and the International Space Station's Canadarm2, Mobile Base System, and the Special Purpose Dexterous Manipulator. The first joint meeting between NASA, TARDEC, and MDA occurred on August 5, 2004 at KSC with discussion and tours to: a) better understand KSC's ice detection and measurement system requirements, b) provide a better understanding of the KSC pre-launch operational environment, and c) determine the "way ahead."

In early 2005, a NASA funded, TARDEC contract was let, and a proof-of-concept system was delivered by MDA and tested in TARDEC facilities in Warren, Michigan. During a 2005 start of year winter period, various concept system operating features and capabilities were tested by TARDEC. Of initial importance was the determination that the system could differentiate between ice and frost and water. Also evaluated was the system's effectiveness in accurately estimating thickness of acreage ice on small ET SOFI test samples provided by NASA-KSC. As time evolved during this year, additional funding was provided by NASA and contracted through TARDEC to MDA to make needed system improvements driven by system use and the analysis of test data.[6]

In early 2006, testing of a prototype (and later improved) system began. Instead of using TARDEC facilities in Warren, testing was moved to better facilities located at nearby Selfridge Air National Guard Base (SANGB) in Harrison Township, Michigan (hereafter referred in this report as Selfridge). This facility was selected because it offered more advantages over any test area available at TARDEC in terms of test distances, environmental control, and overall operating space. During testing the system was found to be able to distinguish between ice and water; however, it a) lacked consistency in ice thickness readings, b) was not linear over test distances, and c) underestimated ice/frost thickness.[2] During this test period, ice camera performance in remote ice thickness accuracy improved through recalibration based on repeated test data collection and analysis followed by recursive software modification. But the system still had not achieved a desired level of ice thickness accuracy.[7] Regardless, this system was a breakthrough in remote ice detection and measurement, and was successfully used during T-3 hour pre-launch inspections for the December 2006 launch of STS-116.

In 2007, additional testing was accomplished at Selfridge and the system was again recalibrated by MDA based on acquired and analyzed test data. Several software recalibrations eventually proved to be successful in increasing system accuracy to the level needed to meet NASA operational and decision-making LCC needs. Also, during 2007 thick shell and thin shell ice ball detection tests were successfully performed and data obtained. This prototype version of the ice camera was found to be in calibration and was validated at Selfridge at the conclusion of testing. Shortly thereafter it was shipped to NASA-KSC for T-3 hour inspection pre-launch support for STS-117. Following post-shipment testing at KSC, the system was again verified as being in calibration, and was collectively felt by NASA, TARDEC, and MDA representatives to be operationally ready. No ET SOFI ice and only one ice ball was visually evident to T-3 hour inspection team members. Unfortunately, the ice camera was not working to full capacity and no data were recorded–however, no target SOFI ice existed anyway during this warm launch period. After repair of a burned strobe high-voltage cable and connector by MDA, the ice camera was successfully used for the August 8, 2007 inspection and subsequent launch of STS-118. Data were obtained and except pan-tilt locking lever problem the system worked well. However, no ice existed or was detected on acreage ice on ET SOFI because of high KSC pre-launch temperatures, but was seen on brackets where ice normally forms regardless of temperature.

Dates	Major Ice Camera Development and Validation Milestones
2004	
1/21/04	SSA signed between NASA-KSC and TARDEC
2/10/04	First test of MDA-Canada ice camera.
3/04	Ice/frost detection and evaluation SOW signed
3/16/04	MDA-Canada delivers improved test system to TARDEC.
3-4/04	TARDEC VPL team investigates various ice detection technologies including a MDA-Canada and Goodrich IceHawk System.
6/1/04	TARDEC working paper and progress report on a "Survey and Comparison of Several Space Shuttle External Tank Ice/Frost Detection and Evaluation Systems' distributed to NASA-KSC. TARDEC team again recommends that a concept system by MDA-Canada offered potential.
6/29/04	Discussions with Charles Stevenson of NASA-KSC of Shuttle technology needs, and ET ice detection and measurement problem and requirements.
8/5/04	First joint SAA/SOW meeting at KSC between NASA, TARDEC, and MDA.
10/04	NASA funds TARDEC to contract with MDA-Canada for proof-of-concept system development.
2005	
2/05	MDA delivers proof-of concept system to TARDEC.
2/22-3/17/05	TARDEC VPL conducts testing of MDA-Canada proof-of-concept system for KSC feasibility and potential use.
6/05	TARDEC working paper and progress report distributed to NASA-KSC.
10/05	TARDEC final test report distributed to NASA-KSC and MDA.
11/29-12/1/05	Meetings and tours held at KSC with TARDEC and MDA team members. A first walk-down with the ice camera at the launch pad was made at this time.
12/05	NASA-KSC funds TARDEC to contract with MDA-Canada for prototype system.
2006	
1/23-3/3/06	Preliminary ice development and procedure creation period using a cryogen test panel at KSC with some TARDEC participation but without an MDA unit.
3/23-4/4/06	First phase of TARDEC-Selfridge testing.

5/31-5/15/06	Second phase of TARDEC-Selfridge testing after hardware problems fixed and software update (algorithm) incorporated.
8/15-17/06	Third and final test phase of TARDEC-Selfridge testing using an upgraded algorithm, bias lamp replacement, and other component modifications made.
8/22/06	Ice camera shipped to KSC to be used in support of STS-115 during T-3 hour inspections, but timing did not allow approval for use. Launch occurred on 9/9/06.
11/04/06	Decision made by NASA-KSC to return the ice camera to TARDEC/Selfridge for recalibration and ice ball testing.
12/7- 9/06	First T-3 hour operational use to support scrub (12/7/06) and successful launch (12/9/07) of STS-116 from KSC.
2007	
1/26/07	Ice camera shipped to Selfridge for additional testing and recalibration by TARDEC/NASA/MDA test team.
1/31/07	Bob Speece of NASA briefed the Level 2 Board on MDA STS-116 performance, and future Selfridge testing plans. There was a positive response to the presentation and ice camera use and no negative comments or concerns.
2/3/07	Supplemental funds transferred from NASA-KSC to TARDEC via MIPR.
2/5/07	Thick ice shell ball molds, Kaman, and the ice ball 12 in. x 12 in. Dewar received from KSC.
2/5-9/07	Phase 1 Selfridge MDA ice panel data collection begins for first MDA recalibration. During this week all NASA provided test panels and equipment arrived.
2/12-16/07	Second week of data collection for MDA recalibration.
2/20/07	Agreement to proceed with testing and addition funding provided to TARDEC by NASA-KSC.
2/23/07	MDA recalibrated using MDA (Gregoris) provided application program.
2/26-3/3/07	Phase 2 data collected of ice thickness reading began to verify MDA recalibration. Thick shell ice ball testing completed.
2/26/07	Hailstorm at KSC caused major damage to ET. A decision was made not to ship the MDA to KSC in early March as planned, but conduct additional ice ball tests.
2/27-28/07	New calibration algorithm loaded into MDA and ice thickness data collection begun.
3/5-9/07	Period of data analysis and no testing at Selfridge.
3/12-4/6/07	Resumption of Selfridge Phase 2 testing and acreage ice and ice ball data collection.
3/27-4/25/07	System sent from Selfridge to MDA-Canada for repairs.
4/26/07	System returned to TARDEC for additional Selfridge calibration verification and ice ball testing.
5/10-18/07	System sent to MDA-Canada for repair followed by return to Selfridge.
5/21-25/07	Test period 3-Phase 3 testing accomplished for calibration verification and ice ball data collection.
5/29-30/07	System shipped to NASA-KSC and received.
5/30-6/1/07	MDA post-shipment testing and system readiness verification at KSC.
6/8/07	Second ice camera used in support T-3 hour inspection of STS-117, but some malfunctions occurred.
6/29/07	MDA unit shipped via TARDEC and received at MDA-Canada for inspection and repair.
7/24-27/07	The MDA was returned to KSC for calibration reverification in preparation for use

	for STS-118 inspections.
8/8/07	Third use of the ice camera during the pre-launch inspection of STS-118. No significant problems were experienced with the system.

Table 1. Key project dates and milestones

4. Physical Principle and Description of the Ice Camera

The MDA ice detection camera operates on the physical principle discovered by the inventor, Dr. Dennis Gregoris, that there is a specific wavelength band over which the electromagnetic (EM) reflectance spectra of ice and water are significantly different.[4,5] These bands are part of what is usually referred to as the near IR or short wave infrared (SWIR) portion of the EM spectrum, between 1.1 and 1.4 microns.

To help understand the nature and design of the ice camera, the following underlying operation is identified by the system developed Dr. Dennis Gregoris of MDA. In operation, the MDA-developed concept and system uses a Xenon strobe, a focal plane sensor array and filter wheel to collect successive images over several sub-bands, and then uses a computed ratio of the reflected intensities from the sample to determine whether or not ice is present. The system then computes and displays ice thickness values. The Xenon near infrared (IR) wavelength strobe is low power (< 100 Watts), and is used to illuminate a surface on which there may be ice–for example on ET SOFI. After illumination of the SOFI surface, electro-magnetic energy is reflected back and focused on an IR (1.1 to 1.4 micron) sensor. The sensor (an un-cooled focal plane array) provides input to a linked on-board computer. The computer processes inputted values and a display unit indicates ice thickness and a color within predetermined range limits.

In operation, the system is affected by the amount of ice (mass) on a surface and does not measure thickness of the ice per se in that way. But the density of ice has an effect on the returned signal and the resultant readings of measured ice thickness. The ice thickness to spectral contrast calibration, therefore, is dependent on and affected by the density of the ice used during system calibration. It is important to realize that the system has inherent limitations in that ice with densities greater than the ice density used during any system calibration will be indicated as having a greater thickness because there is more ice per unit volume. Conversely, lower density ice or frost will appear to be thinner than it actually is.

The physical system and its components (sensor, VHS recorder, and battery power supply) are contained in gaseous nitrogen purged, MDA custom-built enclosures mounted on a NASA-provided, two-wheeled portable cart. The inspection cart with camera and strobe mounted on top is shown in Figure 2.

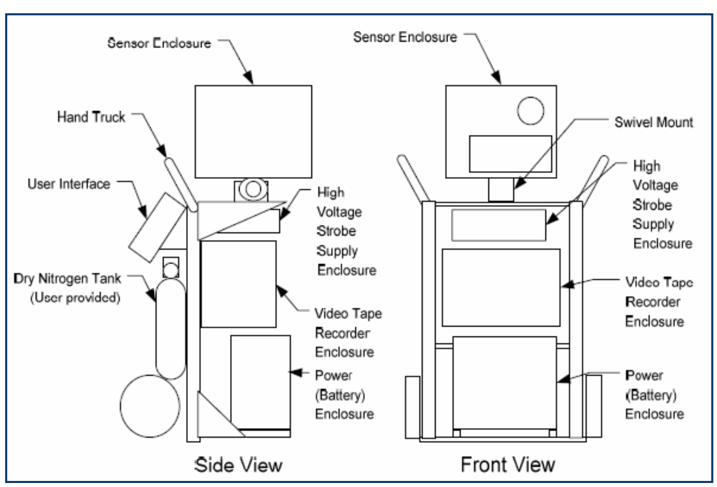


Figure 2. The MDA Ice Camera

The prototype ice camera is pictured in Figure 3. All components are mounted on a NASA-provided wheeled cart to make the unit portable. At the top, an enclosed IR sensor and strobe are supported on a swivel mount that affords horizontal

movement for fine adjustment viewing. Located beneath the sensor/strobe housing is an enclosed high voltage strobe power supply. Beneath it is an enclosed VHS recorder. At the bottom of the cart stack is an enclosed battery that supplies power for all components. At the back of the cart, a user interface display indicates ice contrast and thickness values on a video monitor of the viewed area showing ice thickness as a pseudo-colored display. A switch on the display panel toggles the display from an actual video view of a target area to an ice detection measurement mode and view. Below the display panel is a dry nitrogen supply tank for maintaining a positive pressure inside the VHS recorder and battery enclosures. In total the unit weighs approximately 200 lbs.

Figure 3. The actual MDA Ice Camera

Based on the electromagnetic theory of reflection of light at the surface of a dielectric (ice in this case), the computer estimates ice thickness, if present.[8] For more information on the reflection of light from a thin ice layer and computed spectral reflectance of ice and water versus wavelength see Appendix 1. In operation, a circular "bulls-eye" is shown on the ice camera display and represents the system target area. The bulls-eye encloses the pixels used to calculate the average thickness of ice. The calculation of the number of pixels on a one-in. target is included in Appendix 2. Also included in this appendix are figures showing bulls-eye size versus range, and the number of pixels horizontally on a 2 ft. x 2 ft. SOFI test panel by viewing angle.

Various agreed upon and preset ice thickness ranges are color-coded for display on the operator display monitor. They are (in inches): 0-0.019 grey, 0.020-0.049 green, 0.050-0.059 yellow, 0.060-0.069 red, 0.070-0.249 blue, and 0.250-0.500 magenta. These color indications help the operator interpret quantitatively the information and measured ice thicknesses displayed. The average measured ice thickness from pixels located in the bulls-eye (64 pixels–8 x 8), is displayed on-screen in a field labeled "tkns in" (i.e. thickness inches).

B. TARDEC/NASA Investigation, Development, and Testing History

1. Initial investigation (2004)

a. Investigation objectives and priorities

In response to the SOW,[2] Dr. Meitzler and members of TARDEC's VPL performed a technology search and evaluation of potential electro-optical systems capable of detecting the presence and determining the thickness of ice on STS ET SOFI. Previous research by VPL investigators, following NASA inquiries, indicated that it might be possible to detect and image ice-covered areas with an IR camera. In addition it was realized that methods were needed to detect clear ice that is invisible to the naked eye, and to discriminate between ice, frost, and water on ET SOFI surfaces. The TARDEC team was to test any system(s) found and available using test ice formed on ET SOFI sample panels provided by NASA-KSC. TARDEC, by agreement, was to serve as an independent, unbiased technology evaluation organization for NASA and provide any test results, analysis for technologies/systems found, and recommendations for future system development and testing.[2]

b. Evaluation/test team composition

U.S. Army TARDEC test participants were directed by: Dr. Thomas Meitzler, VPL Team Leader. Team members included: Darryl Bryk, Euijung Sohn, Dr. David Bednarz, Dr. Elena Bankowski, Mary Bienkowski, Kim Lane, and Jennifer Gillis. Dr. James Ragusa served as an independent consultant.

NASA-KSC test participants at Selfridge were: Armando Oliu. Charles Stevenson served as the primary point of contact for engineering and operational information and technical direction. Ron Phelps of the Shuttle Program Office provided test support funding.

MDA test support participants at Selfridge were: Dr. Dennis Gregoris and Denny Maljevac.

c. Test location

This evaluation was conducted at TARDEC in Warren, Michigan. Testing took place partially inside and outside the VPL–through a car-width open access door, and in a small environmental chamber located on site. The primary reason for using inside and outside testing space was that the area inside the lab did not allow longer testing distances (> 25 ft.). In addition, ice formation was more controlled outside the lab in the Michigan winter air. The small environmental chamber provided most controlled conditions for some testing, but did not provide overall ideal conditions.

d. Schedule and milestones

The jointly signed SAA initiated a mutually-beneficial collaborative research investigation clarified under the terms of a SOW for "ice/frost detection and evaluation." Between those events, a potential ice detection and measurement system developed by MDA of Canada was identified that existed in an early stage of conceptual development. During this same evaluation period, two other systems were identified–one by the Goodrich Corp. of Minneapolis, Minnesota named IceHawk, and the other by Dr. Gagnon of the Institute for Ocean Technology and National Research Council of Canada, of St. John's, Newfoundland, Canada. The system of Dr. Gagnon was initially determined to be just a laboratory device with little hope of being compatible with NASA-KSC's needs and operational requirements. For these reasons, only the first two systems were evaluated.

Testing of the MDA and IceHawk systems took place during March and April 2004 in Warren, with a TARDEC working paper and progress report distributed in June[3]. Test results and analysis of the ice camera resulted in a recommendation that this developed technology offered potential to meet NASA's ET SOFI ice detection and measurement present and future needs. In contrast, the IceHawk system would only work *if SOFI had a painted surface* to increase light reflection and polarization for ice detection.[3]

Shortly thereafter, system requirements and specifications were developed, and a contract given to MDA of Canada by TARDEC for the purchase (with NASA provided funds) of a proof-of-concept ice detection and measurement system. The new system, designed and calibrated for SOFI surfaces, was purchased from MDA and was delivered to TARDEC for independent testing and evaluation during the 2004-2005 Michigan winter period.

It is important to understand that since test data was to be shared with MDA (a Canadian firm) throughout this and subsequent testing periods, International Traffic in Arms Regulations (ITARS) liaison for data sharing rules and regulations had to be followed. As a result, all data transmitted to MDA followed approved ITARS procedures. This conformance was supported through NASA approval by William Collins of the Anteon Corporation at KSC. In addition, and by law a copy of all transmitted data are kept for inspection by Ron Phelps of the Shuttle Program Office (PH-P).

Dates	2004 Milestones
1/21/04	SAA signed between NASA-KSC and TARDEC.
2/10/04	First test of MDA-Canada ice camera.
3/04	Ice/frost detection and evaluation SOW signed.
3/16/04	MDA-Canada delivers concept evaluation system to TARDEC.
3-4/04	TARDEC VPL team investigates various ice detection technologies including systems by MDA-Canada, Goodrich, and Tech/Canpolar Inc.
6/1/04	TARDEC working paper and progress report on a “Survey and Comparison of Several Space Shuttle External Tank Ice/Frost Detection and Evaluation Systems” distributed to NASA-KSC. TARDEC team again recommends that a concept system by MDA-Canada offered potential.
6/29/04	Discussions with Charles Stevenson of NASA-KSC of Shuttle technology needs, and ET ice detection and measurement problem and requirements.
8/5/04	First joint SAA/SOW meeting at KSC between NASA, TARDEC, and MDA.
10/04	NASA funds TARDEC to contract with MDA-Canada for proof-of-concept system development.

Table 2. 2004 Agreements and Initial Investigation Milestones.

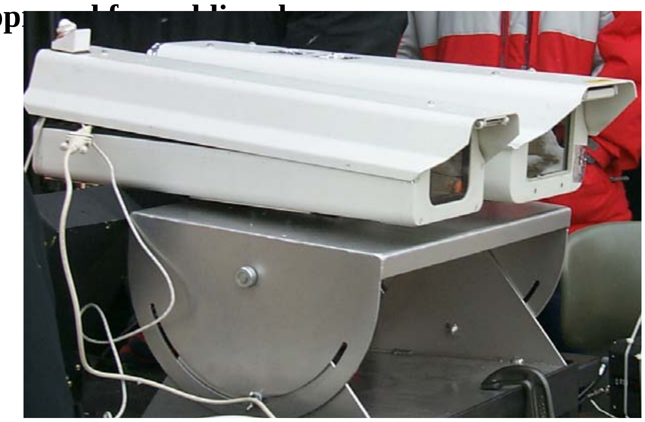
e. Methods, results, and analysis

Methods–For this 2004 testing period, several representative ET SOFI samples were fabricated and provided by NASA to TARDEC researchers for ice detection and measurement testing. To begin experimental work, a 13.7 ft^3 freezer was purchased by TARDEC, and leveled to achieve proper ice thickness formation. Each of the approximate 5½ in. x 5½ in. SOFI samples were numbered for identification with upward direction marked. Ice was formed on the samples by placing them face down (outward side down) in square Teflon-coated 7½ in. x 7½ in. baking pans. Weights were placed on the samples to prevent them from floating when water was poured into the pan. For some samples, ice thickness was controlled by mechanically elevating the foam above the bottom of the pan (more details below). The result was a flat and regular ice surface. For other samples, steps of various depths were milled into the surface. Since the backs of the foam substrates were flat and clear of ice, ice thickness could be accurately determined by comparing obtained before and after ice formation sample measurements. Importantly, this controlled submersion method of ice formation provided a way to measure ice thickness.

It should be noted that the ET foam’s external surface (the exposed side away from the ET metal structure) is convoluted (in this case “bumpy” with foam peaks and valleys). See Figure 4. Actual SOFI has the same texture as the test samples. For this reason, for this first series of tests, ice thickness values were averaged using measurements taken from near the four corners and from the center of the samples. Unfortunately and critical to this investigation, the variance in the height of ET foam surface “bumps” is of the same order of magnitude as the LCC ice thickness limitation–1/16th (0.0625) of an inch.

Figure 4. A section of ET SOFI showing its roughness

NASA NSTS-07700 identifies ice densities of 18-37 lb/ft^3. Typical ice was about 57 lb/ft^3. While VPL researchers were considering how to create low-



density ice (i.e. < 37 lb/ft^3), one of the last snowfalls of the Warren winter occurred in March 2004 and the week before a planned MDA second test period. In anticipation of the need for low-density ice samples for the tests, a container was placed outside the VPL and snow collected. For several samples, collected snow was applied by hand to ET foam surfaces. For other tests, collected snow was applied to various surface shapes for low density simulated ice testing. Figure 5 pictures the concept MDA ice camera. This early version consists of enclosures for an IR sensor and a video camera.

Figure 5. Concept MDA test system with enclosed IR sensor and video camera

Results–At the time of the first ice camera test on February 10, 2004, an incorrect lens was used so the system was not properly focused at the planned camera-to-samples distance of 10 ft. The camera and lens was configured for operation at a distance greater than 15 ft. The close proximity of the samples produced unfocused camera images, which affected the accuracy of the thickness estimate within the framed portions of the samples.

Regardless, ice thickness test results that varied from zero to greater than 0.53 in. were color-coded from black to red, respectively. For this testing, thickness measurements were taken using a manual caliper. Images of the ice-covered ET foam samples were obtained using a Kodak DC265 digital camera. For one test, a milled stair-stepped SOFI sample served as MDA system target with excellent results. Each stair on the sample showed up as a different color, indicating that the system was able to distinguish between different thicknesses of ice. Other SOFI samples had more discrete ice thickness variations. Figure 6 shows partially-ice covered SOFI samples 3 and 2. The corresponding calibrated IR image that is output from the MDA ice camera is shown in Figure 7.

Figure 6. Samples 3 and 2

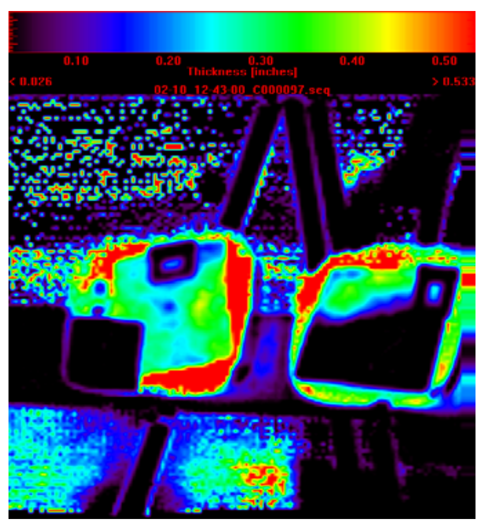


Figure 7. Samples 3 and 2 with ice thickness color codes

MDA representatives visited TARDEC for a second series of system tests on March 23, 2004. For that testing, a piece of plywood was set on an easel on which samples were hung or propped up on edge. As in the first test, the easel was place outside the VPL in approximately 35°F weather. Samples were taken from the freezer, one or two at a time, and scanned individually with most of the foam sample filling the scan area. For identification in the scanned and photographed imagery, plastic numbers were hung near each ET foam sample. Data were taken and manually recorded in specific areas of each sample corresponding to similar areas where ice thickness had been (or would be later) measured (i.e., corner, center, and stepped areas). Manual measurements were changed from a caliper to a Fowler precision gauge used to measure ice thickness of the ET foam samples. Measurements were made on a precision flat optical table.

The second active system tested was a commercial laser road surface sensor (LRSS) manufactured by the Goodrich Corporation of Minneapolis, Minnesota. This system, called the IceHawk, was included for testing purposes because initial discussion with NASA-KSC representatives identified the IceHawk system and suggested that it be evaluated as part of this SOW. After contacting the company and obtaining the loan of a system for a three-week period, testing at TARDEC's VPL was conducted. The system tested was the next generation IceHawk wide-area ice detection system.

This sensor system was designed to indicate the presence of ice or frost on roadways, with other models engineered to detect ice on aircraft surfaces. In operation, the IceHawk system scans a surface by transmitting a laser beam of polarized near-IR light. Ice is detected by analyzing the polarization of the reflected signals. Where ice is present, the returned IR signal is de-polarized. The images produced by the system are color-coded. Ice is displayed in red, snow in blue, and clean surfaces shown in gray. Surfaces that exhibit water are displayed in cyan. However, other objects such as plastic, fabric, grass, etc. may also be displayed in red, blue or light gray. Areas that do not receive enough signal return information are colored black. The IceHawk LRSS is controlled remotely via a laptop computer, which is used to display and interpret road condition images. The LRSS consists of an optical ice detector mounted above and in close proximity to the surface of interest. When the LRSS performs a scan of the surface, data are saved in an image file on the hard drive of the LRSS. The image can then be downloaded to a computer, using Microsoft Windows 95™or 98™ operating systems, and a RS-232 or modem interface.

To test the operating effectiveness of the IceHawk system with respect to distance, VPL investigators placed a large painted ET foam sample (provided by Goodrich) at varying distances (17, 30, 35, and 47 ft.) from the system. These distances were chosen because of the space available in the TARDEC lab. The IceHawk system requires that ET foam be painted to increase light reflection and polarization for ice detection. The resolution seemed to get worse at greater distances, and the ice/frost delineation didn't improve.

It was noted with the current IceHawk system that thin ice is displayed as frost. The system also misidentifies non-ice/frost materials to be frost–like wood and diffusing materials. To test the frost/ice delineation, a painted SOFI sample was modified with machine screws to allow ice thickness to vary from 1/16 to 1/4 in.–top to bottom. Initially, IceHawk readings showed gray (defined as "clear" of ice) pixels in an upper middle region of the sample and red (ice) below. As time progressed (about 20 minutes), the gray area encompassed the top half of the sample with red in the bottom half. This change in color indicated that the system saw a change in ice thickness. However, it misreported the upper area as clear when ice was present.

TARDEC testing confirmed earlier somewhat unsuccessful testing results obtained by Goodrich in their Minneapolis facilities using NASA supplied ET foam samples. In this earlier company test it was determined that ET foam did not provide the needed polarization effect needed to accurately measure ice thickness. The company did claim, however, that their systems are excellent in identifying clear ice on many surfaces–but that ET SOFI is a problem.

VPL investigators next moved the IceHawk system to an environmental chamber located at TARDEC. See Figure 8. The chamber had a region of frost, which accumulated on one of its walls, and the IceHawk system correctly characterized it as snow (blue). In summary, the IceHawk system tested was unable to determine the exact thickness of ice on an ET SOFI surface or frost.

Figure 8. View of environmental chamber and IceHawk system

Analysis–A technology search initiated by members of TARDEC resulted in a selection of two electro-optical systems as candidates for investigation and testing. A third (conceptual) system was not considered viable. Neither of the two active tested systems (MDA or IceHawk) produced the exact same measurements as a precision height gauge for simulated ET foam ice thickness. In addition, neither system accurately and reliably supported the pre-launch constraint for an ET ice thickness measurement limit of 1/16th (0.0625) of an inch–the primary objective of this SOW testing. However, there may be benefits to using either the Goodrich system or the ice camera to detect the presence of clear ("black") ice because in some cases, ice on any part of the ET or Space Shuttle may be transparent and not visible to the naked eye.

The Goodrich IceHawk system, however, was found by VPL investigators to only measure the presence of ice and frost under some conditions when the foam *was painted*. The system as presently designed, did not provide accurate and quantitative measures of ice thickness on *unpainted* ET foam samples–a primary condition of this research effort. If only a determination of ice or frost on other more mechanical areas of the Space Shuttle or pad systems is needed such as LO2 bellows or supports, this system may be of value for NASA pre-launch operations.[3]

The ice camera offered a promising approach for the approximate measurement of ice thickness. The higher correlation between the lab gauge readings and ice camera measures is an indication that the physics of the method used was probably valid. There was also a strong indication by the manufacturer that the system could be adjusted to meet the pre-launch constraints of ice thickness and size for pre-launch conditions given more time and development. However, since the ice thickness limit is of the same order of magnitude as the variability of the "bumpy" ET foam surface, this poses a problem for precision measurements, consistency, and confidence in the "go" or "no-go" launch decision process. While statistical analysis showed that there is a significant difference between the ice thickness determination of the ice camera and height gauge measurements, this

difference may not be of practical importance and within the range of acceptability for other ice/frost KSC applications.

The TARDEC VPL comparison of these systems, testing, and analyses was the subject of the first report dated June 1, 2004 submitted to NASA-KSC.[3] As a result of that report, VPL investigators and NASA engineers determined that a system developed by MDA-Canada offered the greatest potential to support tanking tests and T-3 hour ice debris team detection and evaluation activities on the launch pad prior to STS launches.[3]

2. Proof-of-Concept Ice Camera Testing (2005)

a. Test objective and priorities

The primary objective of testing an initial MDA proof-of-concept system at TARDEC, during a February and March 2005 winter period in Warren, was to test various operating features and capabilities of MDA's system to differentiate between water, frost, and ice. Testing also focused on the system's effectiveness in accurately estimating thickness of acreage ice on ET SOFI test samples provided by NASA-KSC. The ultimate goal was that the ice camera could through its design, remotely detect and reliably measure ice formed on the SOFI surface of the ET of NASA's Space Shuttle during occasional tanking tests and required pre-launch T-3 hour inspections. Four MDA test objectives were jointly developed and mutually agreed upon prior to ice camera delivery and test initiation. Specific objectives for this 2005 test period were:

Objective 1: Determine whether the system can detect low-density ice (LDI: 18-37 lb/ft^3), and how results compare with normal density (freezer) ice (NDI) with a density of approx. 57 lb/ft^3.

Objective 2: Determine if water composition used to make ice (distilled vs. rain vs. Michigan tap water) has any effect on the system to determine the presence of ice on SOFI, and whether the MDA camera, an IR-based system, can discern between ice and cold water.

Objective 3: Determine if the system can detect and measure the thickness of ice greater than or less than 0.0625 in. (1/16 in.), and if the estimation of ice thickness is distance independent.

Objective 4: Determine the accuracy of the system's ice thickness estimation.

b. Test team composition

U.S. Army TARDEC test participants were directed by Dr. Thomas Meitzler, VPL Team Leader. They included: Darryl Bryk, Euijung Sohn, Dr. David Bednarz, Dr. Elena Bankowski, Mary Bienkowski, and Kim Lane. Dr. James Ragusa served as an independent consultant.

NASA-KSC test participants at Selfridge were: Armando Oliu, Bob Speece, and John Blue. Charles Stevenson served as the primary point of contact for engineering, and technical direction. Ron Phelps of the Shuttle Program Office provided test support funding.

MDA test support participants at Selfridge were: Dr. Dennis Gregoris and Denny Maljevac.

c. Test location

As in 2004, MDA testing and evaluation occurred at TARDEC in Warren. Testing took place partially inside and outside the VPL–through a car-width open access door. In this way ice formation was more controlled outside the lab in the winter test period.

d. Schedule and milestones

After delivery of a proof-of-concept system by MDA, TARDEC researchers began testing of the system using an agreed upon test plan with identified objectives. A relatively short period of testing between late February and mid-March 2005 resulted in data collection followed by analysis of system performance. In June, the unit was shipped to KSC for launch pad elevator fit checks and human factor studies on access platforms of the launch structure and ramps on the Mobile Launch Platform. These were the same launch facility areas that would be used during normal T-3 hour inspections. During this on-site study it was found that the unit, although bulky and a little hard to move and position, could be integrated into T-3 hour inspections.

Dates	2005 Milestones
2/05	MDA delivers proof-of concept system to TARDEC
2/22-3/17/05	TARDEC VPL begins ice camera testing for NASA-KSC feasibility and potential use.
6/05	MDA unit shipped to KSC for familiarization and evaluation and possible use to support the STS-115 launch.
6/05	TARDEC working paper and progress report distributed to NASA-KSC.
10/05	TARDEC final test report distributed to NASA-KSC and MDA.
11/29-12/1/05	Meetings and tours held at KSC with TARDEC and MDA team members. A first walk-down with the ice camera at the launch pad was made at this time.
12/05	NASA-KSC decides to fund TARDEC to contract with MDA-Canada for a prototype system development. Funding was to follow when approved.

Table 3. 2005 MDA Milestones and Testing

e. Methods, results, and analyses

Methods–The SOFI samples provided to TARDEC from NASA were used to test the ice camera. Some samples were used previously for the 2004 tests, and some were new or modified. Samples were labeled for identification and "up" orientation with a permanent marker as in earlier tests. Similar to tests performed in 2004, ice was applied to the samples by laying them foam side down into Teflon coated baking pans. Inverting the samples in the water in pans produced a uniform ice surface that was flat and regular, and the Teflon surface provided easy sample removal. As mentioned in the NASA 2004 test report,[3] besides making a smooth regular surface, this method of inverting the SOFI in a pan provided a way to more accurately measure the ice thickness because the backs of the samples were devoid of ice. Ice samples were made in the freezer by placing weights (rocks and plastic containers of ice) on top of the samples to prevent them from floating, and water was added to a desired height. Since some samples were milled flat or in steps with only 1/32 in. face clearance, air bubbles were dispersed from under the samples by lifting one side out of the water, and then slowly lowering it back into the water, thereby forming a wedge to drive out bubbles. For testing purposes, milled SOFI was considered equivalent to natural (as-sprayed) samples, and this assumption was later confirmed to be valid, as sample data did not vary enough to required averaging of natural SOFI test points using the ice camera.

For imaging with the ice camera, some SOFI samples were placed on a plywood board and easel. The board and associated metal brackets were painted black to reduce

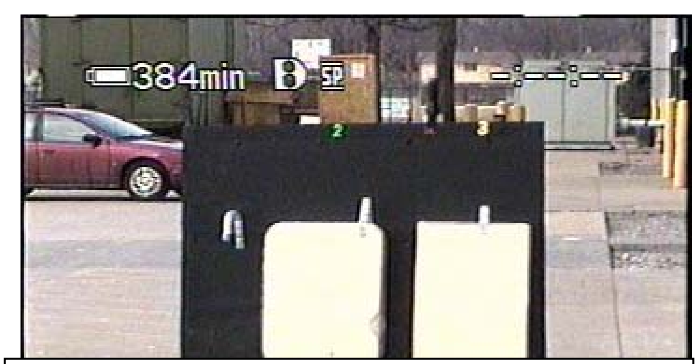


Figure 9. Iced SOFI samples shown supported on an easel for measurement

any background noise. See Figure 9. Hooks were attached to some samples for hanging on the board, and a 1-5/8 in. ledge at the bottom of the board held others up. Large samples were set on the ledge and attached to the top with flexible metal straps. Since the MDA camera works in the IR, normally visible labels would be invisible. Plastic refrigerator magnet numbers/letters were hung near each sample as they were imaged for identification later in video recording.

MDA camera data was taken of specific areas of each sample corresponding to similar areas where ice thickness had been (or would be later) measured with the dial gauge (e.g. corners, center, and stepped areas). In all tests the MDA onboard a videocassette recorder (VCR) was used to record the imagery. In later tests, the audio output from the camcorder was input to the audio input on the MDA onboard VCR for simultaneous audio (e.g. voice) recording to provide additional information during the tests.

The original plan was to use an environmental chamber located at the TARDEC test site that would allow precise humidity and temperature control. However, malfunctions of that facility required a revision in plans. There was a possibility of using the environmental chamber at Ford Motor Company's Science Labs, but that would have entailed a lot of movement of the ice detection system, which would have caused numerous complications. The only viable option was to take advantage of the cold weather that occurs during the winter in Michigan. With the arrival of the ice camera, tests were conducted from February 22 to March 17, 2005.

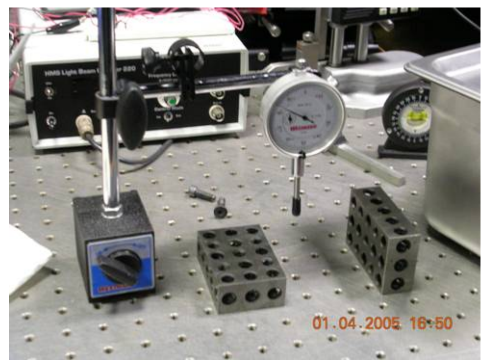


Figure 10. Dial gauge and calibration blocks

For this series of tests, manual ice thickness measurements were made using a Westward dial indicator gauge (range: 0 to 1 in. x 0.001 in., accuracy: ±0.002 in.) with magnetic base and extension rods to measure ice thickness on the SOFI samples. See Figure 10. Readout was from an analog dial display to 0.001 in. The reading was "zeroed" by a spring adjustment rod. Since it only had one in. of range, an optics quality 1 in. x 2 in. x 3 in. calibration block, and if needed, a precision cut 1/4 in. aluminum plate, were used to adjust the zero position with the spring rod. Since the dial gauge probe had a consistent spring tension, the applied contact force was consistent, and therefore so were measurements. To reduce ice melting, the metal dial gauge probe tip was covered with a plastic (screw thread) cover and Kapton tape. This configuration probe tip measured about 1/4 in. in diameter. (Kapton tape was recommended by the MDA engineers as a very good insulating material.) A larger Styrofoam probe (2 in. x 1.5 in. x 0.5 in. thick) was also used for Objective 1 tests to measure an average surface area height of frost, and to spread the measuring force over a larger area to help keep from deforming the frost.

The dial gage was used to determine height to calculate ice thickness for Objectives 1, 3, and 4, but in another way to measure samples for Objective 1. The dial gauge was set to measure horizontally against the SOFI sample attached to the side of a small liquid nitrogen (LN2)-filled aluminum container. A steel L-shaped corner brace was bolted to the optical table to be used as a template to reposition the dial gauge base. The gauge was "zeroed" in the template after LN2 was poured into the container, but before ice started accumulating. Later, after ice was formed, thickness was measured by repositioning the gauge base in the template. With the inherent accuracy of the

dial gage being ±0.002 in., and the variability in repeatability of measurements found to be about ±0.005 in., a cumulative inaccuracy of about ±0.007 in. was estimated.

For Objective 3, samples were measured by laying them back-side down onto an optics table or onto calibration blocks. The very large samples had irregularly shaped foam back surfaces. To prevent rocking, a weight greater than 6 lbs., was set on top of the sample in the center, to stabilize it during measurements. A pad of Styrofoam was placed on the sample first, to isolate the ice from the metal weight, and to spread out the force. This Styrofoam base was also used when there was no ice. The weight was removed when measuring the center region, but there was assumed to be no rocking present when the probe spring force was applied to the center (this may not have been a satisfactory solution–see Objective 4 conclusions below). The dial gauge was "zeroed" and then several heights were recorded at semi-random positions (as chosen by the experimenter). Ice samples were quickly measured by gliding the probe over the surface and recording a range of heights in the specified regions.

For coarse and milled un-iced samples, five semi-random measurements were taken in each corner and the center, except for the stepped samples, for which was recorded three points on each step (e.g. left, center, and right). The measurements were done with and without ice so that the ice thickness was the difference of the two measurements. During MDA scans, samples were usually measured before and after MDA measurements to quantify any ice loss that may have occurred. As mentioned previously, the natural coarseness of the SOFI surfaces is quite irregular, approaching 1/8 in. to about 3/16 in. of depth between peak and valley, therefore it was difficult to accurately measure these samples, and for that reason these measurements should be considered approximations.

Specific objectives, results, and analyses–Test results and subsequent discussions with NASA, TARDEC, and MDA representatives led to the conclusion that the system should be modified to enhance its performance.[6] NASA decided that an improved ice camera might have the potential to make a significant contribution to their ice detection and measurement needs, and add to their toolbox of methods and visual inspection capabilities and experience. The resultant system was now considered to be a prototype ice detection and measurement system. More specifically and with regard to the four objectives jointly developed and mutually agreed upon with NASA-KSC representatives, results for this 2005 testing period in Warren were as follows:

Objective 1: Determine whether the system can detect low-density ice (LDI: 18-37 lb/ft^3), and how results compare with normal density ice (NDI).

Results: NASA representatives reported that the density of ice buildup on the ET at KSC has been in the range 18-37 lb/ft^3 (i.e. LDI).[9] Normal density ice (NDI), as made in a freezer, is typically about 57 lb/ft^3 (and is not normally formed on the ET during KSC pre-launch operations). For this objective, a SOFI sample was attached to the outside of a metal container, which was filled with liquid nitrogen (LN2) in order to grow LDI on the SOFI sample. Preliminary attempts proved to only yield frost of density less than 18 lb/ft^3. In subsequent trials using various techniques (enclosure, humidifier, water spray), LDI was attained in two recorded trials.

Analysis: It was observed that the ice camera detected LDI and frost, although with inconsistent readings. To compare LDI to NDI measurements, it was thought, that numerical comparisons could be made from later objective testing with NDI. Importantly, it was observed that frost and LDI thickness was considerably underestimated by the ice camera, in comparison with actual physical

measurements. Later observations indicated that LDI measurements were also underestimated in comparison to NDI measurements. Therefore, the ice camera was found to be ice density dependent in its estimate of ice thickness. That is, lower ice density seems to cause the ice camera to further underestimate ice thickness when compared to NDI. Thus, there would be risk associated with relying on the ice camera solely for *quantitative* ice thickness measurements.

Objective 2: Determine if water composition used to make ice has any effect on the system to determine the presence of ice on SOFI, and whether the MDA camera, an IR-based system, can discern between ice and cold water.

Results: Three ice/water compositions were tested: distilled water, local Michigan rain water, and tap water. It was evident from the MDA visual display that the system was able to determine the presence of ice on SOFI samples regardless of water composition, and could distinguish cold (47 ° F) water on SOFI from frozen ice on SOFI. Water appeared as "undefined" (pseudo-colored black) on the ice camera monitor.

Analysis: Due to the nature of these tests, only *qualitative* results (and not *quantitative* data) are presented to answer objective 2. Through visual inspection, the ice camera consistently distinguished between ice and cold water independent of whether the ice and water was from distilled water, Michigan rain water, or tap water. From these *qualitative* observations, it was concluded that the composition of test water from different sources did not play a role in detecting water or ice made from the three water types. However, it should be pointed out, that the ice camera cannot discern water from other "undefined" materials (e.g. wood, metal), because it had been calibrated for SOFI ice detection only.

Objective 3: Determine if the system can detect and measure the thickness of ice greater than or less than 0.0625 in. (1/16 in.), and if the estimation of ice thickness is distance independent.

Results: The 0.0625 in. threshold LCC is important (as mentioned earlier) for a "go–no go" launch decision because of the danger of falling ice onto flight crew windows, orbiter thermal tiles, and Reinforced Carbon-Carbon (RCC) wing panels. Also, launch structure access for viewing and sensing ice forming ET areas vary, and for that reason distance independence is important. NASA-KSC's launch pad configuration dictated distances of 25 to about 75 ft. for T-3 hour ice debris team inspections. For this phase of VPL testing, agreed upon test distances were 25, 50, 60, and 75 ft.

A precision analog dial indicator gauge was used to verify actual ice thickness. The dial gauge and MDA estimates for ice thickness differed appreciably in these tests. The ice camera was found to be somewhat unstable in its ice thickness estimates, leading to inconsistent data. MDA (Dr. Gregoris) has stated that some of the noise or instability may be attributed to the long time delay between strobe flashes (three seconds), and spatial fluctuation of the strobe beam pattern that are present in this proof-of-concept version of the system.

Analysis: Empirical evidence indicated that the ice camera could detect ice less than or greater than 1/16 in. However, the system showed a lack of consistency in ice thickness measurements by 10-15 percent. Testing also indicated that the ice camera was not able to accurately estimate ice thickness independent of distance (i.e. as distance changes for fixed ice examples, so do thickness measurements).

Objective 4: Determine the accuracy of the system's ice thickness estimation.

Results: A dial indicator gauge was used to measure actual ice thickness. As a point of validation, an assumption must be made that ice thickness determination by use of the dial indicator gauge is accurate to some tolerance greater than the ice camera. More specifically, coupled with the dial gauge manufacturer's specifications (±0.002 in.) and human repeatability (±0.005 in.), a cumulative inaccuracy of ±0.007 in. is estimated with the device. The overall uncertainty of the ice camera, as stated by the developer, is ±0.020 in. Therefore, measurements with the dial gauge are significantly better than the ice camera and make the dial gauge a good reference.

Subsequent data analysis, however, showed inconsistencies that prompted a reexamination of gauge measurements made on SOFI samples 2B and 3B. Later measurements on sample 2B (without ice) showed differences of 0.03 in. from previous measurements. The origin of these errors is not certain, except to note, that these B samples had irregular bottom surfaces, and therefore may have made an unstable measuring platform.

Analysis: The system did not have consistent readings even for fixed samples and distances. Inconsistency and inherent noise in the current proof-of-concept system, coupled with melting ice samples, and sample measurement difficulty for samples 2B and 3B, prevented satisfactory testing and data analysis. Without system modification and additional testing, it was recommended that the proof-of-concept ice camera be used only as a *qualitative* device for locating the presence of ice, rather than a *quantitative* ice measurement device for determining the relative thickness of ice.

Overall 2005 Testing Results–The proof-of-concept ice camera, as tested in the TARDEC VPL during the brief February 22-March 17, 2005 test period was determined to be primarily a thin ice detection system that has the potential to *qualitatively* detect the presence on ET SOFI of: a) low-density ice (18-37 lb/ft^3) common to the KSC launch environment, and b) ice of thickness ≥ 0.0625 in. (the NASA LCC). The system can clearly distinguish between areas of SOFI that are covered by cold water versus those areas that are covered with NDI-type ice, and where NDI is present to at least 0.020 in. thick. The system does not appear to be affected by water composition, either for detecting water, or detecting ice made from various sources of water.

However, the present ice camera: a) did not consistently determine ice thickness for target areas in the range of distances measured (25 to 75 ft.), b) did not measure linearly for these distances, and c) considerably underestimated NDI and LDI/frost thickness, as found on actual ET SOFI test sample surfaces.

The system was also found to be unstable during VPL testing, that may be due to the long time delay between strobe (flash lamp) flashes and fluctuation in the strobe beam pattern, both of which MDA claims to have reduced with modifications in a subsequent prototype. The system also had sensor distance limitations, which are a function of strobe light intensity, sensor efficiency, and target surface reflectance and absorption. Whether, the physics inherent in the ice camera design is the limiting factor, or whether these issues may be resolved in subsequent engineering optics, sensor, and software modifications, remained to be proven. Through this testing it was realized that there are major contributors to ice camera ice thickness measurement inaccuracy. They are:

- Ice densities used to calibrate the ice camera
- Ice density of the test ice surface and the experimental measurement of density
- Viewing angle

- Strobe frequency
- Signal level related to distance
- System noise

Based on test results, analyses, and understood limitation of the MDA proof-of-concept system it was concluded that the system, in its present proof-of-concept state, would have to be used with caution by the NASA-KSC ice debris team for T-3 hour inspections to indicate areas where ice may be present on ET SOFI. TARDEC investigators believed that this proof-of-concept system should only be used as a *qualitative*, rather than a *quantitative* ice measurement device to indicate the location and relative thickness of ice.[6]

At this stage of the ice camera's development, it was *not* recommended that the system be relied on as the sole indicator of ice thickness, but that further human inspection would be necessary. In spite of these limitations, the system showed potential to solve a capability need that NASA-KSC had for ice detection and measurement. Regardless, this system was a breakthrough in remote ice detection and measurement. The system was shipped to NASA-KSC for familiarization and use, with the target system delivery and use being Space Shuttle *Discovery*'s return to flight scheduled for July 2005. Testing of a MDA-developed proof-of-concept system at TARDEC in Warren and at KSC in 2005 confirmed that a portable remote sensing ice detection and measurement system was a possibility, but that additional work was needed by MDA to greatly improve the system's performance.

3. Modified Prototype Ice Camera Testing (2006)

TARDEC was again requested to contract with MDA (with NASA funds) for modification of the proof-of-concept system. As a result an improved prototype system was delivered to TARDEC on March 16, 2006. As major improvements, the system had a stronger IR strobe and an improved power supply and electronics.

a. Test objective and priorities

Discussion between NASA, TARDEC, and MDA resulted in an extensive plan for the testing of the prototype ice camera. Testing was *initially* segmented into three phases for implementation as described in a February 2006 test plan. Emphasis was initially placed on: a) acreage ice, b) thick ice, and c) density comparison. Planning resulted in six primary test objectives (1 through 6). As testing progressed, five additional objectives (A through E) were identified. Specific primary and additional objectives of this 2006 testing period were:[7]

Primary objectives were:

Objective 1: System accuracy–Determine if the ice camera can accurately measure ice in and around the LCC thickness of 0.0625 in. and maximum ice thickness values from 0.250 and 0.500 in.

Objective 2: Viewing angles–Determine if the ice camera accurately measures ice at viewing angles varying from 90 to 20 degrees (as measured from the plane of the SOFI).

Objective 3: Range–Determine if the ice camera accurately measures ice at distances between 25 and 80 ft.

Objective 4: Color displays–Determine if the ice camera ice thickness and color displays are correct and accurate. Agreed upon ice thickness color operator displays to be verified regardless of

range are: 0-0.020 in. grey, 0.021-0.050 in. green, 0.051-0.060 in. yellow, 0.061-0.070 in. red, 0.0701-0.250 in. blue, and 0.251-0.500 in. magenta.

Objective 5: Illumination–Determine if ambient low level and reflected full sunlight illumination extremes affect ice camera accuracy.

Objective 6: Density comparison–Determine how the ice camera performs measuring normal density KSC ice (30 to 40 lb/ft^3 as identified by NASA) when compared to measurements made of high density (freezer) ice > 50 lb/ft^3.

Additional test objectives were:

Objective A: As-sprayed SOFI panel testing–Determine if as-sprayed (natural) SOFI ice measurement and thickness tests differ from milled SOFI, and if it was reasonable to make the assumption that their respective IR reflectances are equivalent.

Objective B: Frost growth tests–Determine the accuracy of the ice camera to detect frost thickness and ice under frost. NASA has defined frost as ice having a density of < 18 lb/ft^3.

Objective C: Low-density tests–Determine if low-density ice (> 18 and less than 30 lb/ft^3) is different from ice of greater density.

Objective D: ET primer test–Determine how thin and thick ice-covered metal with and without Koropon paint (the primer of the ET tank surface under SOFI) reflects ice camera IR signals when compared to SOFI.

Objective E: Salt water test–Determine if there is any significant difference between tap and ocean salt water used for ice development.

b. Test team composition

U.S. Army TARDEC test activities and participants for this 2006 test period were directed by: Dr. Thomas Meitzler, VPL Team Leader. Team members included: Darryl Bryk, Euijung Sohn, Mary Bienkowski, Kim Lane, Rachel Jozwiak, Ivan Wong, and Gregory Smith. Dr. James Ragusa served as an independent consultant. TARDEC responsibilities remained to continue as an independent testing agency for NASA-KSC to determine if the prototype system performed consistently and accurately within its planned operating parameters.

NASA-KSC test participants at Selfridge were: Thomas Moss, Bob Speece, John Blue, and Scott Lockwood. Martin Scott tested NASA-purchased 3D laser scanning and imaging equipment during the test period. Charles Stevenson served as the primary point of contact for engineering and operational information and technical direction. Ron Phelps of the Shuttle Program Office provided test support funding.

MDA test participants at Selfridge were: Dr. Dennis Gregoris and Denny Maljevac. Participating at MDA-Canada for project and software support were David Parry, and Simon Yu, respectively.

Responsibilities varied for individuals with the TARDEC team serving as the nucleus of the test and analysis team, while NASA, namely Tom Moss, actively supported the effort for extended periods of time. As required, MDA provided engineering, hardware, and software services as needed under a separate support contract.

c. Test location

Instead of using Warren, Michigan facilities, testing of the prototype ice camera took place in a nearby Selfridge Air National Guard Base (SANGB) hanger (Building 1424) located in Harrison Township, Michigan–hereafter referred to as Selfridge. Fortunately, the hangar was under the control of another U.S. Army TARDEC group and space was available for testing with their agreement. This site and facility was selected because they offered protection from the elements, a test distance of more than 100 ft, electrical power and other utilities, and meeting facilities. Now available was space for all planned test activities, and storage for assorted test equipment, SOFI samples, cryogen Dewars, and the ice camera.

Of course, a large environmental chamber would have been preferable for this type of testing, but such a facility was not available or cost effective at TARDEC or at any other facilities surveyed and contacted. As a substitute, the SANGB hangar was suitable for testing because it could be used for a range of environmental conditions (e.g., 35-86°F and 30-75% relative humidity), if the SOFI samples were prepared properly (i.e. sufficiently thin), and suitable ice forming techniques were employed. The drawback to the unregulated ambient environmental conditions in the hangar was that poor test ice samples could be created if not properly formed, thus yielding invalid results. It was found, however, that the Selfridge hangar was much better and far more preferable than TARDEC facilities for ice formation and testing.

d. Schedule and milestones

During early January through early March 2006, activities were planned to develop and become familiar with ice creation procedures using a Dewar and larger SOFI panels. This work took place at KSC using a cryogenically cooled (LN2) test panel with support from some TARDEC personnel. The MDA ice camera was not used for this KSC familiarization period.

Formal ice camera ice detection and measurement system testing by TARDEC/NASA occurred at Selfridge in three phases from March 23 to August 17, 2006. It should be noted that these tests were conducted during the spring and summer, and *not* the winter period when ice creation and stabilization would have been more desirable.

As planning proceeded, NASA also expressed an interest in the detection and possible measurement of regularly-formed ice on vehicle vent lines, metal brackets, and engine areas after the ET has been loaded with cryogens. It was also known that a new LCC for ice balls was in development and was about to receive NASA Shuttle Program approval. After testing was completed, the plan was to send the prototype ice camera to NASA for engineering analysis during T-3 hour inspections for ice formation on the ET during an actual Shuttle countdown. If this ice camera was determined to be worthwhile, it was planned that NASA would fund the development of one or more operational systems for future use and replacement of the prototype system.

First phase testing from March 23 to April 4, 2006 began after delivery of the prototype ice camera to TARDEC, and delivery of a new KSC-provided 2 ft. x 2 ft. cryogen test container (CTC), representative SOFI samples (two milled and two as-sprayed), and miscellaneous needed test equipment. A combined TARDEC, NASA-KSC, and MDA team was involved in this testing using jointly developed test objectives and procedures.

Following first phase testing, a second phase test period took place between May 30 and August 11, 2006. Ice camera maintenance and software modification occurred on May 30, 2006 and

included the replacement of the connector at the positive flash lamp terminal wire and transformer junction, replacement of the flash lamp (strobe), and a new thickness algorithm software upgrade. The software modification was created and uploaded to improve the performance of the system and its accuracy readings. The algorithm was developed by MDA based on March-April 2006 contrast (ice thickness-related) measurement data. A software upload was made at Selfridge by MDA personnel.

As testing progressed, TARDEC and NASA revised this initial plan to create a MDA Ice Detector Test Plan dated June 13, 2006 that included the above listed test objectives and some additional ones. This revised plan was far more ambitious and was intended to greatly expand testing to include, in addition to various ice thicknesses, distances, and viewing angles for SOFI ice, objectives for frost growth, ice of various densities, ice formed on metals, and ice made from Atlantic Ocean salt water that may be more representative of ice formed in the salt air environment of KSC.

A third phase and final test period occurred during August 15-17, 2006 after the ice camera software was again modified using an upgraded algorithm, bias lamps replaced, and other component modifications made. This was the last test period before the system was shipped to NASA-KSC on August 22, 2006 for use in support of the STS-115 launch scheduled for mid-September. However, MDA ice camera use was not approved by NASA in time to support this launch.

On November 4, 2006, NASA-KSC, TARDEC, and MDA agreed that future MDA ice camera recalibration testing should be accomplished at Selfridge during the winter period. The ice camera was approved for use for the planned early December launch of STS-116. T-3 hour inspections using the ice camera took place during a launch scrub on December 7th, and for the successful launch two days later on December 9th. The overall schedule of significant 2006 events is contained in Table 4.

Date	2006 Milestones
1/23-3/3/06	Preliminary ice development and procedure creation period using a cryogen test panel at KSC with some TARDEC participation but without an MDA unit.
3/13/06	KSC provided cryogen panels, SOFI samples (milled and as-sprayed), and supportive test equipment received at TARDEC. Ice formation and procedure development began at Selfridge with NASA participation.
3/16/06	Prototype ice camera arrived at TARDEC from MDA-Canada and moved to Selfridge for testing.
3/23-4/4/06	First phase of TARDEC-Selfridge testing.
5/30/06	System repaired and recalibration by MDA.
5/31-6/15/06	Second phase of TARDEC-Selfridge testing after hardware problems fixed and software update (algorithm) incorporated.
7/15/06	MDA support service contract approved and system recalibrated and bias bulbs replaced by MDA.
8/15-17/06	Third and final test phase of TARDEC-Selfridge testing using an upgraded algorithm, bias lamp replacement, and other component modifications made.
8/22/06	Ice camera shipped to KSC to be used in support of STS-115 during T-3 hour inspections.
8/23/06	Ice camera received at NASA-KSC. Two bias bulbs replaced at NASA-KSC by MDA-Canada representatives. The system was considered ready for operational use in support of the STS-115 launch.

9/6/06	STS-115 launch date, however, the MDA was not yet approved for use. Approval sought for STS-116 T-3 hour inspections.
11/4/06	Decision made by NASA-KSC to return the ice camera to TARDEC/Selfridge for future testing and system recalibration following the launch of STS-116.
12/7/06	First operational use of the ice camera to support an STS launch. However, this STS-116 launch was scrubbed very late in the countdown.
12/9/06	Second operational use of ice camera to support the successful launch of STS-116.

Table 4. 2006 Prototype Ice Camera Milestones and Testing

e. Methods, results, and analysis

Methods–Since testing occurred at Selfridge during the 2006 summer period, procedural control for ice formation and maintenance was difficult at times to maintain, and some experimental noise and test errors may have occurred. However, the test setup used LN2 to provide adequate ice for testing. A significant change during this test period was that for all testing, a Kaman eddy current device was used to determine formed ice thickness on test panel samples as the basis of comparison with MDA readings. However, frost thickness determination was made using a thin film gauge.

The following assumptions were made to accomplish this testing and to improve data collection:

- Use of LN2–LN2 is a close enough cryogen to substitute for LO2 and LH2.
- SOFI–KSC created SOFI samples are equivalent to operational ET SOFI.
- Kaman and ice camera accuracy–This eddy current measurement device was assumed to be the most accurate method of measuring test ice thickness, and the standard of comparison. Accordance to vendor information its variability is approximately ±0.001 in. The ice camera was considered by its developer to have a variability of ±0.008 in.
- Milled vs. as-sprayed SOFI Samples**–**There would not be any significant difference between the two types of NASA provided SOFI samples–milled and as-sprayed. This assumption was important because milled samples have the advantage of providing more accurate ice thickness reading using the Kaman unit.
- Test ice density–Ice can be formed for testing purposes with a density range of 30 to 40 lb/ft^3 for testing to simulate nominal KSC ice densities. Test ice densities were generated and maintained from ice formation procedures developed jointly by NASA and TARDEC, and were verified through ice weight and volume determinations. Note: It was initially assumed that ice density was constant through creation and through the test day; however, it was later discovered that the density of ice decreased as the ice was built up during test periods.
- Ambient illumination levels–Selfridge hangar light illumination or lack of it will make no difference in data collection or results.
- Water type–As with all previous testing, tap water was acceptable for frost/ice formation. (Except later when various types of water were tested including sea water.)

Since test procedures and equipment were significantly changed and improved during this test period (and standardized for use during 2007), the following more in depth information is provided for a better understanding of test methods and equipment used.

Ice formation–Liquid nitrogen (LN2) was the cryogen used to chill the CTC (illustrated in Appendix 8) needed to support ice growth on the SOFI sample panel surface. Sanding techniques in

combination with a Wagner airless water sprayer was used to produce ice on the chilled SOFI surface and also to assist when creating desired ice thicknesses during testing. The rate of ice growth and thickness was controlled through a jointly developed TARDEC/NASA water spraying/misting process using the sprayer. During Selfridge testing ice layers were slowly built up to reach the desired ice thicknesses. The ice camera was used to collect data on ice test thicknesses as ice grew to the next test thickness. After final ice thickness was reached and measured, the density of the ice was determined. For more procedural details see Appendix 9 for Experimental Techniques.

Ice thickness determination–Ice thickness was determined and compared to the ice camera though the use of a NASA-provided Kaman eddy current thickness measurement tool. A three-inch diameter Kaman head unit was used. (Reference the Kaman unit being used below in Figures 11 and 12). Pre-test SOFI baseline thickness was determined using the Kaman unit and its digital readout after liquid cryogen was present in the test Dewar, but prior to the presence of ice. After ice was formed, the Kaman was again placed on top of the test ice and a new measurement made. Ice thickness was then determined from the difference of the two readings.

Figures 11 and 12. Images of Kaman unit on milled SOFI showing location grids (left) and Kaman digital readout unit

Figure 11 pictures the Kaman unit with a three inch head being used to measure ice thickness on a milled ice-covered SOFI test sample. Fishing line strung on a metal picture frame form a grid of test cell reference locations. See Appendix 5 for test panel coordinate references. Figure 12 shows the Kaman being zero-calibrated on a flat test surface in the background, and in the foreground its digital readout with two calibration rings sitting on top.

Test measurement sequence–The general sequence was: Kaman measurements for specific target areas followed by ice camera readings. However, it should be realized that the purpose of this first test sequence was to collect data on ice thickness and not comparison of Kaman vs. ice camera data just yet. For the purpose of testing and this report, by definition the Kaman was used as the *measurement* standard (except for frost measurements which used a thin film gauge), and the ice camera test device was used for *readings* to be used for accuracy comparison.

Ice density–Ice density was determined through an analysis of ice formed on a 2 ft. x 2 ft. milled SOFI test panel sample. Note that milled SOFI was used instead of as-sprayed SOFI to control a test variable. Ice weight was calculated by comparing the weight of the SOFI test panel sample ice free (dry) to the weight of panel with ice (of various ice thicknesses) using a scale. The volume of ice was calculated by determining its average thickness (using the Kaman) and the approximate 2 ft. x 2 ft. area of the ice surface. Density was then calculated as the weight of ice (test panel with ice minus test panel without ice) divided by the volume occupied by the formed ice (average thickness times area). The target density range of the 2 ft. x 2 ft. test panel SOFI ice was 30 to 40 lb/ft^3 (consistent with nominal ice densities formed at KSC on the ET). This target density range was achieved and maintained through the development of a TARDEC/NASA misting procedure and process, and verified periodically. Reference Appendix 4 for specifics.

During testing it was discovered that ice density decreased as layers were built, so the earliest-formed thinnest ice had the highest densities, and the later developed thickest layers had the lowest densities. See Appendix 12 for statistical error analysis of ice density. Consequently, the end-of-test-day measured ice density for a test sample was lower than earlier thin layer densities. These ice density variations during the tests increased ice camera error, which was calibrated with mid-density ice (approx. 35 lb/ft^3).

The following are the focused activities of the expanded tests and parameters:

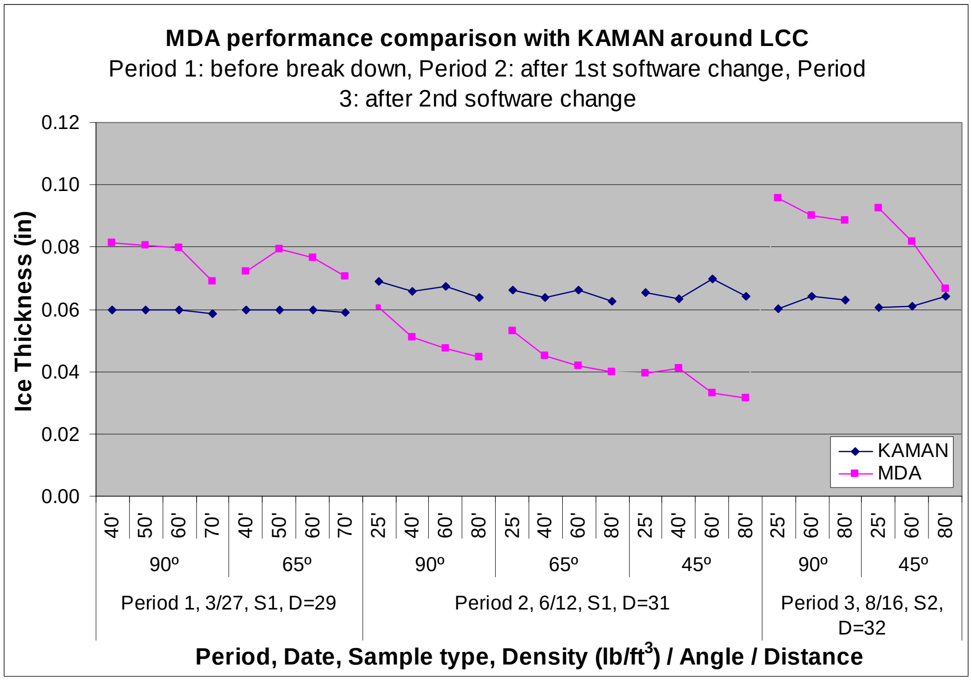
Testing parameters–Testing required the collection of data for various angles (20, 30, 45, 65, and 90 degrees) and reasonable distances (25, 40, 60, and 80 ft.) for ice thicknesses of 0.020, 0.050, 0.060, 0.070, 0.250, and 0.500 in. At the extreme configurations of 25 and 80 ft. at 90 and 30 degrees for each ice thickness, additional illumination data were recorded with the tungsten-halogen solar-simulation light. Measurements were taken at an angle nearly tangential to the panel and also at an angle nearly perpendicular to it. The light was physically moved to different positions prior to the ice camera measurement. Its relative position to the test panel was kept constant by using a piece of string set to the desired length that was tied to the lamp handle, and the lamp was placed on a cart with wheels. The set distance for simulating the Florida solar radiance was determined earlier during NASA testing by Tom Moss at KSC. The initial target ice density was 30 to 50 lb/ft^3 for testing–later revised by NASA as 30 to 40 lb/ft^3 for nominal density KSC ET ice.

As-sprayed SOFI panel testing–Limited testing of as-sprayed SOFI was required using a complete set of test angles and distances with 0.0625 and 0.075 in. thick ice of 40-45 lb/ft^3 density. Viewing angles were 90, 65, and 30 degrees, and distances of 25, 60, and 80 ft. As-sprayed SOFI is, as the name implies, SOFI in an original form and representative of the type of foam used on the ET. The purpose of this test is to verify that the results of using machine-milled SOFI can be used as a substitute for as-sprayed foam.

Test notes:

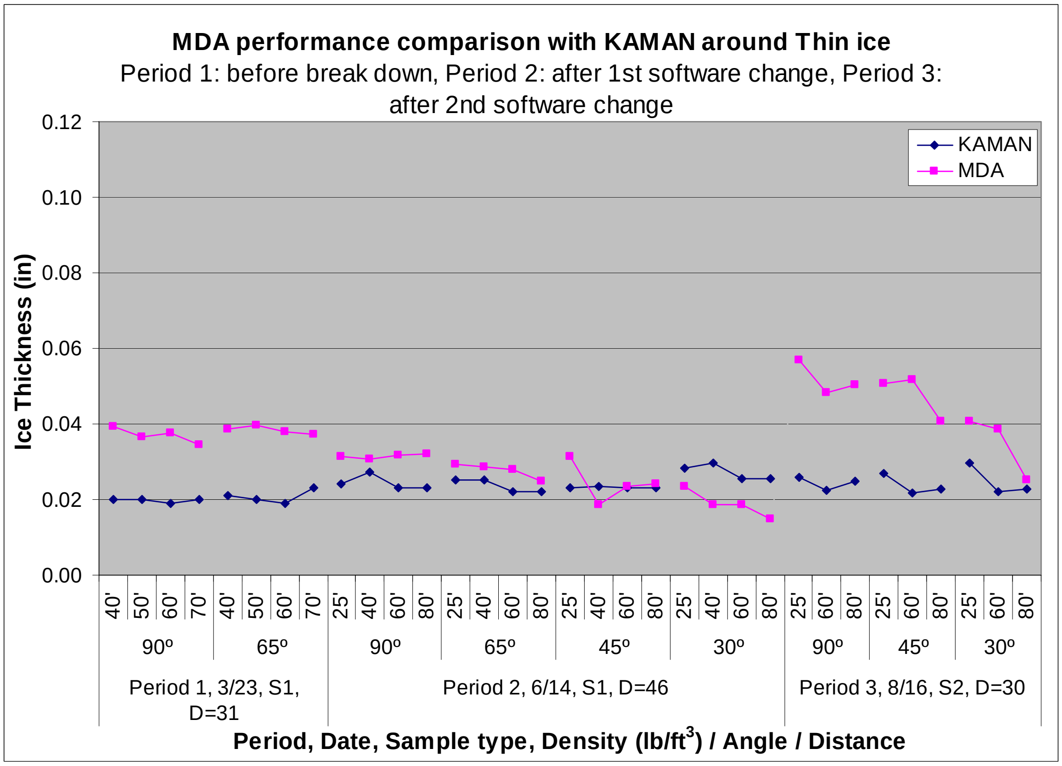
1. Rather than attempt to maintain the exact target ice thickness, two grid locations were usually chosen to bracket the target ice thickness for measurement for each test: one approximately 0.005 in. below the targeted ice thickness and one 0.005 in. above it. (Reference Appendix 5 for test panel grid coordinates).
2. The Kaman was considered the standard *measurement* for ice thickness comparison with ice camera *readings*. The thin film thickness gauge was the standard for frost growth measurement comparison with ice camera readings.
3. When necessary, limited tests were extended to further characterize ice camera operation.
4. All tests were completed using milled SOFI unless otherwise stated. Ice densities were targeted, but exact values using the development method could not be guaranteed since densities were not known until the completion of data collection or the test day.

Results and analyses–Experimental data were collected and organized for analysis. These data were then presented in various forms to display and support test results and conclusions reached. Charts were developed to indicate Kaman measurements and ice camera reading versus distances, viewing angles, densities, and illumination levels to provide readers with an overall visual and numerical representation of collected data. The final test report includes three important Selfridge test summary charts from the 2006 test report that are repeated here.[7] These charts are important because they summarize multiple periods of test data.



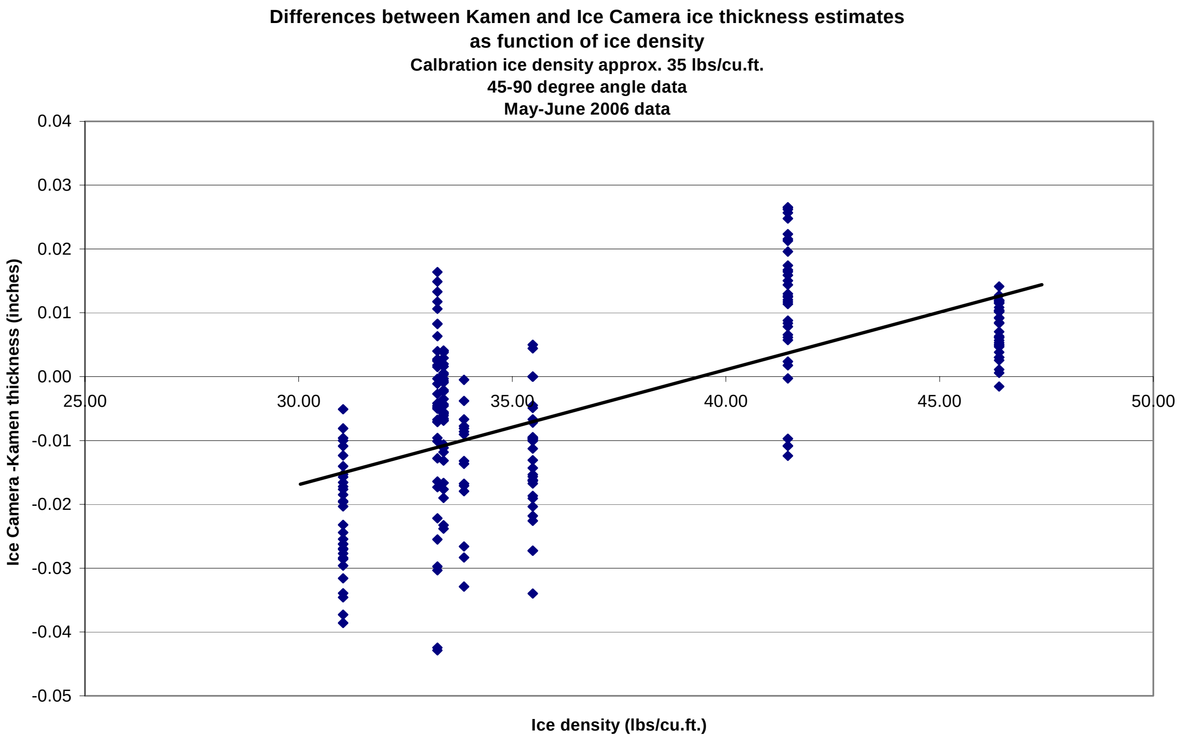
Results–Rather than being a test in itself, the first summary chart shown above is a consolidation of sample data from the *three test periods* before and after ice camera software upgrades. The first software upgrade occurred between the first and second test period, and the second at the start of the third period of testing. The objective of this combined data is to determine the accuracy of the ice camera prototype system around the LCC of 0.0625 in. All of the test densities are close to or within the nominal KSC densities of 30 to 40 lb/ft^3, and viewing angles are restricted to 90, 65, and 45 degrees. Represented is a full range of viewing distances from 25 to 80 ft.

Analysis–The data show that throughout the three test periods, the Kaman readings were consistent and linear, and because of the results received, the experimental ice preparation method and hangar environmental conditions must have been fairly consistent on these test days. Throughout the three periods, the ice thicknesses measured with the Kaman unit were mostly within the LCC to about ±0.005 in. It should be noted that ice camera readings prior to the first recalibration and after the last, resulted in ice camera values above the Kaman values–the most desirable accuracy error for safety. The middle test period, after the first recalibration, were below Kaman measurement–the less desirable error with regard to accuracy. Importantly, for the three test periods, the data show that within a particular value of the angle of incidence of the ice camera (with respect to the SOFI test panel surface), accuracy usually falls off monotonically and approximately linearly with increasing distance to the test panel. This is a clear indication, with ice thickness and density relatively constant, that viewing angle and distance are critical variables that contribute to ice camera accuracy.



Results–Like the earlier chart, the following second summary chart is a consolidation of sample data from the three test periods before and after ice camera software upgrades. The objective of this combined data is to determine the accuracy and agreement between the Kaman and ice camera for ice thinner than LCC ice, around 0.020 to 0.030 in. Two of the test densities are the nominal KSC densities of 30 to 40 lb/ft^3, but one is for a density of 46 lb/ft^3 (approaching high density freezer ice and higher than the nominal KSC density). For this data representation, viewing angles are 90, 65, 45, and 30 degrees, and a full range of viewing distances from 25 to 80 ft.

Analysis–Again the Kaman unit shows that the ice preparation technique and the procedural use of the Kaman measurement were consistent over the three test periods. For thin ice around 0.020 in, the angle appears to be less important and in fact, the angle and distance do not cause disagreement between the Kaman and ice cameras, except in the third period after the latest calibration. During the second period, the ice camera agreed within ±0.005 in. of ice thickness measurements even for high-density ice of 46 lb/ft^3 except at 30 degrees where ice camera readings were below Kaman measurements. The first period shows a greater difference, but at least the operation of the ice camera is linear over distance and angle. ***These data indicate that with a good calibration, the ice camera has the potential (within limits), to respond linearly over distance and angle for thin ice.*** It was hoped that this consistency could be extended to greater LCC ice thicknesses.



Analysis–The above summary chart, provided by ice camera developer Dr. Dennis Gregoris, shows the relationship between ice at various densities versus the ± difference between ice camera (ice camera) readings and Kaman measurements. Reading and measurements were derived from May-June 2006 data, with the ice camera calibrated with 35 lb/ft^3 density ice, and viewing angles varying between 45 and 90 degrees. Test ice data from about approximately 31 to 47 lb/ft^3 density ice were used to construct this chart.

Indicated on the chart is the difference between the Kaman measurements and ice camera thickness readings, as a function of the ice density measured at the *end* of the test day (which means that ice density is likely lower than stated). The reason being that it was observed by Selfridge test personnel that ice density at the end of the test day (when it was routinely measured) was lower than ice density formed at the start of daily testing. The MDA thickness function was derived from spectral contrast measurements of different ice layers with densities of 30-35 lb/ft^3. The above results (summarized and represented by a straight line) indicate that the ice camera overestimates the thickness of higher density ice (> 40 lb/ft^3), and underestimates the thickness of lower density ice (< 36 lb/ft^3).

Specific primary and additional objectives and their analyses for this 2006 testing were:

Objective 1: System accuracy–Determine if the ice camera can accurately measure ice in and around the LCC thickness of 0.0625 in. and maximum ice thickness values from 0.250 and 0.500 in.

Analysis: It should be noted that the accuracy of the system *decreased* after the first test period (March 23–April 4, 2006) as a result of system recalibrations made at the beginning of the second and third test periods. In general, system accuracy was not as good as was expected, and the present modified prototype ice camera did not meet quantitative accuracy expectations for "go-no go" decisions. It was felt that the ice camera should be considered *semi-quantitative* in capability at the

time. However, it is a good *qualitative* tool in that it does consistently indicate the presence of ice of all measured thicknesses, and also can differentiate between ice and water as earlier tests confirmed. In spite of two software upgrades to improve the accuracy of ice thickness measurements, system performance did not improve, but in fact, decreased.

It should be recognized, however, that this prototype system successfully demonstrated a proof-of-concept. It should also be realized that the system was tested partially during the summer in Michigan and under extreme conditions–viewing angles of 20 degrees, distances to 80 feet, and using ice of various densities–some outside normally expected KSC conditions. While 20 degrees and 80 ft. were testing extremes, they are within the theoretical and physical limits of the ice camera. Also there was only limited testing of ice at 0.250 to 0.500 in. ice thicknesses on SOFI, and this only occurred on a bare metal (non-Koropon-primed) sample plate. Some thick ice creation (0.250 in.) and testing, however, occurred during the third test period on SOFI. However, a scarcity of 0.250 and 0.500 inch thickness data for these very high SOFI ice thicknesses made ice camera calibration and values suspect, but what was important were ice thicknesses at or near the LCC.

Also the issue of ice optical clarity has been raised, since there were test periods when test ice "glazed" and became cloudier over time. This could be another test variable except that usually ice cloudiness is more of a compounding factor in the visible portion of the EM spectrum and less so in the near IR associated with ice camera operations. However, this issue needs further discussion, more analysis, and possibly additional testing.

Objective 2: Viewing angles–Determine if the ice camera accurately measures ice at viewing angles varying from 90 to 20 degrees (as measured from the plane of the SOFI).

Analysis: In general, the ice camera accuracy is better (and operationally more acceptable) at viewing angles of 90 to 65 degrees. What most of the data showed during the three Selfridge test phase periods is that at viewing angles of 30 degrees or less (especially at greater distances) the ice camera usually indicates undervalued ice (i.e. ice is thinner than it actually is), which is the worst error for NASA operational pre-launch decision making. At these extreme angles, agreement between sensed and actual ice thickness decreases with angle and distance as might be expected, because less IR light is reflected back to the MDA sensor. The present ice camera does not have a way of compensating for extreme angles or distance.

Objective 3: Range–Determine if the ice camera accurately measures ice at distances between 25 and 80 ft.

Analysis: Generally, the ice camera functions more accurately at closer distances to the ice surfaces, but some test results under certain conditions do not always show that consistently. Regardless, it is better that use of this prototype system be limited to operational use between 25 and 50 ft. Note: NASA has restricted MDA use to not closer that 25 ft. because it is an IR emitting device.

Objective 4: Color displays–Determine if the agreed upon ice camera ice thickness range and color displays are correct and accurate. Ice thickness color displays to be verified regardless of distance are (in inches): 0-0.019 grey, 0.020-0.049 green, 0.050-0.059 yellow, 0.060-0.069 red, 0.070-0.249 blue, and 0.250-0.500 magenta.

Analysis: The ice camera does accurately display ice thickness for *its* readings in appropriate colors, and color displays seemed to be properly coordinated with ice thickness limits. It should be realized that these color displays might not indicate the *actual* thickness of ice viewed, since coloring is based on its thickness measurements, which may have limited accuracy. Until the ice cameras accuracy is improved, it would be better to use the ice camera and its capabilities in a limited way for detecting the LCC ice by using general color displays, i.e., green is good, yellow is caution, and red, or blue, or magenta indicates ice of unacceptable thickness.

Objective 5: Illumination–Determine if ambient low level and reflected full sunlight illumination extremes affect ice camera accuracy.

Analysis: Some testing was accomplished with Selfridge hangar lights on and off. It was found that hangar light illumination or lack of it made no difference in data results. Tangential tungsten-halogen illumination did not seem to matter much either as far as ice thickness measurements were concerned. However, there were some indications that direct 90 degree light does affect ice camera readings, since several "V" patterns of ice camera readings appeared. An initial theory proposed by Dr. Meitzler was that direct illumination to the SOFI surface seems to affect MDA readings by causing some reflected light to shine into the MDA sensor causing reading to indicate that ice is thinner than it actually is. However, this is likely not the case. System designer Dr. Dennis Gregoris of MDA explained that because of the strobe, the ice camera is immune to ambient lighting, and in fact works both day and night. The ice camera uses the strobe to remove the effects of ambient light since ambient light is not frequency modulated in the same manner as the strobe. However, if the reflected strobe signal is weak due to distance or low surface reflectance, then the gain will be increased to compensate for the low reflected signal. If the ambient light is strong, its intensity will also be increased by the camera gain so that total light signal nears the saturation point and the detector output becomes non-linear. This would cause the contrast to decrease and hence the calculated thickness would decrease as well. Generally speaking, the higher the gain, the greater the decrease in the contrast/thickness–and ice thickness value. The problem still remains, however, of how to remove the cause of the "V" patterns in the data.

Objective 6: Density comparison–Determine how the ice camera performs measuring normal density KSC ice (30 to 40 lb/ft^3 as identified by NASA) when compared to measurements made of high density (freezer) ice > 50 lb/ft^3.

Analysis: There was very little success in consistently forming ice > 50 lb/ft^3 for comparison purposes. There was, however, some ice generated greater than 48 lb/ft^3. In general, it was found that the ice camera was less accurate in determining ice thickness of higher density ice. However, ice of the nominal KSC densities (30 to 40 lb/ft^3) does result in the most accurate ice thickness ice camera readings. It should be noted that it was initially assumed that ice density was constant through creation and during the test day; however, it was later discovered that the density of ice decreased as the ice was built up during test periods.

Additional test objectives:

Objective A: As-sprayed SOFI panel testing–Determine if as-sprayed (natural) SOFI ice measurement and thickness tests differ from milled SOFI, and if it was reasonable to make the assumption that their respective IR reflectances are equivalent.

Analysis: ***There was no evidence to conclude*** that there was a significant difference in these SOFI surfaces. For both, there is significant IR reflection of light for high angles, e.g. 30 degrees for

ice at the LCC thickness (0.0625 in.). There was limited testing of an as-sprayed SOFI sample during the second test period with results similar to milled samples of earlier and later periods. In addition, the system designer does not believe there should be any significant difference in reading because of how the ice camera works.

Objective B: Frost growth tests–Determine the accuracy of the ice camera to detect frost thickness and ice under frost. NASA has defined frost as ice having a density of < 18 lb/ft^3.

Analysis: The limited frost testing data obtained during testing indicated that: a) frost thickness is experimentally difficult to accurately measure because of its ice/air composition (fragility) using the Kaman, but better when using a wet film thickness gauge (WFTG), b) the ice camera sees frost as thinner ice or not at all, c) the ice camera cannot differentiate ice and frost layers, and d) readings of ice thickness under frost are somewhat inaccurate because the system sees frost as thin ice.

Objective C: Low-density tests–Determine if low-density ice (> 18 and less than 30 lb/ft^3) is different from ice of greater density.

Analysis: There were several instances where low-density ice was formed and data collected using Kaman measurements and MDA readings. Frequently, there was a better agreement for ice of this density (and closer distances between the ice sample and the ice camera) than ice greater than 50 lb/ft^3. In general, it is better to use the present ice camera, with its current calibration, on low or medium density ice within the nominal KSC range between 30 and 40 lb/ft^3 with its current calibration.

Objective D: ET primer test–Determine how thin and thick ice-covered metal with and without Koropon paint (the primer of the ET tank surface under SOFI) reflects ice camera IR signals when compared to SOFI.

Analysis: As a result of tests performed during 2006 test phases, there is no evidence that the ice camera behaves any different from IR reflected on Koropon-primed metal or SOFI (milled or as-sprayed). This is an indication that the ice camera should be useful for ice detection and measurement on both SOFI and metal surfaces for either thin or thick ice. However, accuracy on bare metal, Koropon-primed, and SOFI surfaces is still a prototype ice camera issue.

Objective E: Salt water test–Determine if there is any significant difference between tap and ocean salt water used for ice development.

Analysis: There is no evidence that the ice produced from salt water was significantly different than tap water used during this series of tests except in appearance. A side by side test of salt and tap water during this period was not made. But test data from both types of water individually were equivalent even though ice made from salt water was visually different. Ice camera ice thickness linearity is still present with both water types, and extreme viewing angles and distances still greatly reduce reading accuracy for both water types.

Summary of 2006 Selfridge Test Results–There were several specific ice camera characteristics to be tested as described in an initial February 2006 test plan and through the implementation of developed test procedures for Selfridge testing. The goal, which was met, was to determine how the modified prototype ice camera might function for ice detection and use during ET tanking tests and T-3 hour inspections. Accomplishment of the test objectives was intended to

determine how well the ice camera performed consistent with NASA-KSC requirements and needs, and launch site operational parameters and limitations.

As a result of testing during 2006 it was found that the modified prototype ice camera: a) did not initially demonstrate system or component stability, and b) it lacked accuracy in ice thickness readings throughout testing. During initial Selfridge testing, the system was found to be somewhat unstable with respect to component reliability. Because of system problems such as IR strobe unreliability and user display discoloration, on several occasions MDA personnel were called in. Corrective actions were taken to replace components, add extra insulation, and resolder connections. On two occasions, the system required an upload of software for recalibration improvement. Because of these changes, the original prototype system delivered at the start of the testing period had to be repaired and modified through development and periodic software uploading. In all fairness, it should be realized that the system was operated during a testing period far longer than would be expected during normal intended use, and was still a prototype system that evolved as a proof-of-concept system made from off-the-shelf and laboratory components and parts.

The two major ice camera recalibrations accomplished during Selfridge testing were: one performed in April 2006 using March-April data, and the other in July 2006 using March, May, and June data that excluded 20, 30 and 45 degree angles and used ice densities in the 31-35 lb/ft^3 range. The later recalibration was optimized to reduce the average difference between the Kaman and ice thickness model and was set to slightly overestimate ice thickness to be conservative. However, the August 2006 measurements did not appear to be as accurate as earlier data and they tended to significantly overestimate ice thickness. The major changes to the camera in that time period were the strobe (flash lamp) and the bias lights. Strobe flash calibration was verified, but the effect of a bias light change has not been quantified. The test procedures and measurement protocol also changed during this later testing, so it is not clear whether it was the ice camera or test conditions that had any affect on some test results. It was probably a little of both.

f. MDA support for STS-116

The modified prototype ice camera was shipped to KSC for support of STS-116 T-3 hour inspections and operated by NASA engineer Bob Speece–once for a launch attempt on December 7, 2006 and again for the successful launch on December 9, 2006. See Figure 13. NASA representatives indicated that during the second launch countdown, there were high winds up to 35 knots in the area. Wind at that speed restricted ET ice acreage formation by reducing condensation on the ET. However, two hours prior to launch the wind died down to acceptable levels, and the MDA was taken to the pad.

Figure 13. Ice camera on launch pad being used in support of STS-116

Acreage ice was successfully detected by Bob Speece on the ET above the white room level using the ice camera. In addition, three small ice balls formed on a cable tray and were observed. The hydrogen umbilical also had a 2 ft. by 6 in. ice patch. Other ice was detected in areas as the unit was moved. Human factor problems were encountered as anticipated, with the manual movement of the MDA on the narrow sloped, grated, and four foot wide work platform connecting the Fixed

Service Structure (FSS) and the Rotating Service Structure (RSS) because of its weight (approx. 200 lbs.). Clearly the unit needs to be reduced in weight to improve its portability and usability.

On the lower levels of the Mobile Launch Platform (MLP), it was found hard to rotate the MDA head up beyond 45 degrees to view engine vents and other targets of interest. The reason was that the prototype had a tilt viewing angle range limitation of 0 to 45 degrees from the horizontal. However, the swivel mount was later replaced by MDA for more movement to approximately 55 degrees, and the planned operational MDA unit has a specified range of 0 (nominal) to 70 degrees. (See future operational system requirement A-5 in Appendix 13.) Also, it was found that it is better to pull rather than push the unit up a MLP ramp slope. Some artifact flashes were also noted on the user display panel. In spite of these noted limitations, data were collected and results reviewed.

Based on TARDEC test results from 2005 and 2006 test periods and STS-116 use, NASA concluded that if improved in accuracy, the MDA-Canada developed ice detection and measurement camera had the potential to contribute to NASA inspection capabilities and decision support for ET SOFI and other ice locations. Importantly, to improve capabilities, the system needed to be recalibrated to support nominal KSC operating inspection conditions. To improve ice measurement accuracy, MDA representatives concluded that the ice camera needed a stronger strobe and power supply, more robust electronics, and additional improvement features. TARDEC was again requested to contract with MDA (with NASA funds) for further modification of the prototype system tested in 2006 at Selfridge.

4. Prototype Ice Camera Testing and Recalibration (2007)

a. Test objective and priorities

There were two major test objectives established for the 2007 Selfridge test period. The first, with the highest priority as established by NASA (Stevenson), was to collect sufficient data for another recalibration and verification of ice camera readiness for use in support of the launch of STS-117. By agreement with NASA, data collection (and eventual recalibration) was limited to a viewing distance of 25 to 50 ft. between the ice covered SOFI test panel and the MDA unit, and an 80 degree viewing angle for various thicknesses of ice up to and including the LCC thickness of 0.0625 in.

The data collection, recalibration, and verification objective for this 2007 Selfridge test period required that a test plan and procedures be developed to accommodate this identified primary priority for acreage ice (SOFI) detections and accurate measurement improvement. Specific ice camera recalibration and system accuracy verification was to be accomplished around the following KSC operational parameters:

- Primary MDA readings taken from 50 ft.
- Viewing angle of 80 degrees as measured from the surface plane of the SOFI.
- Ice target thicknesses of 0.040, 0.050, 0.060, 0.070, 0.080, and 0.100 in.
- Emphasis placed in and around the LCC thickness of 0.0625 in.
- Test ice density maintained in the nominal KSC density range of 30 to 40 lb/ft^3 with an ideal test density of 37 lb/ft^3.

The second major test objective for the 2007 test period was to determine how effective the ice camera was in detecting and perhaps measuring ice thickness on thick and thin shell ice balls of various diameters that can form on bare SOFI surfaces. While it was understood that the present

MDA prototype system was not originally designed or built for ice ball applications, what was desired was to determine just how well the system would perform for ice ball detection and possible shell thickness measurements. This would be another test of the limits of the system.

This latter secondary test priority was driven by a recently developed, evolving, and approved NASA LCC for ice balls. The driver for ice ball testing would expand NASA's operational requirements for the ice camera from *just* ET SOFI acreage ice detection and measurement, to expanded capabilities for MDA ice ball and mass determination under the new LCC. This LCC has resulted from: a) observed ice balls on bare ET SOFI, b) results from other NASA test locations, c) a better understanding of ice ball formations and compositions, and d) present and evolving launch constraints. NASA (Stevenson) indicated that an ice ball LCC presently consisted of pictures and tables for thick and thin ice ball shells and conditions that are acceptable or not. Text and pictures exist as an ice ball-related presentation showing the shapes and locations of ice balls on the ET, as well as formed ice balls.

Since ice balls were unknown to TARDEC and MDA team members, there was a need for an education by NASA of ice ball morphology–defined for our purpose as the study of the form and structure of ice ball growth and composition. NASA provided the following information to the team concerning ice balls. They can: a) form because of cracks or inclusions in SOFI, b) initially have a donut-shaped base on SOFI, c) be hemispheric or odd shaped, d) be classified as either thin or thick shelled, e) be formed on frost or covered with frost, and d) have a *frost* center and are *not* solid ice. Further ice ball discussions described ice ball formation and testing that had been accomplished at NASA's Stennis Space Center. The ice balls tend to form initially as a domed donut would, and as a result are thicker at their bottoms. As the ice ball grows because of increased cold, the dome gets thicker toward its top and may be 1/4 in. thick at its apex. Eventually the ball becomes frost filled.

For the secondary objective, NASA requested that thin shell ET ice ball detection tests and possible thickness measurement be accomplished within this 2007 test period. Because of the variability of ice ball morphology, it was agreed that "practical' operational parameters and limits be defined for test ice balls before they could be created and tested. NASA (Stevenson) confirmed that of critical importance to KSC were ice balls with a diameter of approximately 2 in. However, the maximum ice ball diameter per the LCC is 2.3 in. At that diameter ice ball mass exceeds an acceptable limit if it should break off and strike a sensitive Orbiter surface. Ice balls of size 1 in. and 3 in. are still of importance to understand the limits of ice camera detection and measurement capabilities.

The following is a summary list of identified operational parameters and limits under which the modified MDA ice camera was expected to function in detecting ice balls:

- Primary MDA readings taken from 25 to 50 ft.
- Viewing angle of 90 degrees as measured from the surface plane of the SOFI.
- Hemispheric ice balls of diameters of 1, 2, and 3 in., but the target size is 2.3 in.
- The density of ice balls varies from 47 lb/ft^3 for thick shell ice balls to 27 lb/ft^3 for thin shell ice balls.

b. Test team composition

U.S. Army TARDEC test participants were directed by: Dr. Thomas Meitzler, VPL Team Leader. Team members included: Darryl Bryk, Euijung Sohn, Mary Bienkowski, Kim Lane, and Gregory Smith, and Michele Charbeneau. Dr. James Ragusa served as an independent consultant.

NASA-KSC test participants at Selfridge were: Thomas Moss, Bob Speece, Scott Lockwood, Chris Iannello, and Tony Bartolone. Charles Stevenson served as the primary point of contact for engineering and operational information and technical direction. Ron Phelps of the Shuttle Program Office provided test support funding.

MDA test support participant at Selfridge was: Dr. Dennis Gregoris, and participating at MDA-Canada for project support were David Parry, Denis Maljevac, and Simon Yu.

Responsibilities varied for individuals with the TARDEC team serving as the nucleus of the test and analysis team. TARDEC was to continue as an independent testing agency for NASA-KSC to determine if the modified ice camera performed consistently and accurately within its planned operating parameters. NASA representatives actively supported testing efforts as needed at Selfridge and at KSC. As needed, MDA provided supporting services on request under a separate contract at Selfridge and at MDA-Canada.

c. Test location

All 2007 testing of the recalibrated (modified) prototype ice camera again took place in a hangar (Building 1424) located at Selfridge Air National Guard Base (SANGB). This was the same hanger used for 2006 MDA modified prototype ice camera testing.

d. Schedule and milestones

The ultimate objective of this year's test activities was to recalibrate the ice camear to improve its accuracy when compared to Kaman measurements, and secondarily determine if thin shell ice balls of various diameters (i.e. 1, 2, and 3 in.) could be detected by the ice camera and perhaps ice thickness determined. Testing was accomplished during this 2007 period in three phases with the ultimate goal of using a recalibrated and verified ice camera for STS-117–the next Space Shuttle launch. The Selfridge test and launch schedule was extended by a Florida hailstorm in late February that caused extensive damage to the ET and delayed the launch until June. The chronology of 2007 Selfridge testing, data collection, recalibration, and shipment to KSC to support the launch is included in Table 5.

The 2007 Selfridge testing activities began after the ice camera was returned to TARDEC/Selfridge in January 2007 after its December 2006 use during two STS-116 pre-launch inspections. Of importance was a briefing to the Shuttle Program Review Board in late January by Bob Speece of NASA on STS-116 ice camera results. This briefing led to subsequent approval to again use the ice camera for STS-117 pre-launch inspections.

Phase 1 testing occurred during February 2007. Formal ice camera data collection for system recalibration and thick ice ball testing began at Selfridge after delivery of a NASA-provided 2 ft. x 2 ft. cryogen test container (CTC), representative SOFI samples, and other loan equipment. A drawing of the CTC is included as Appendix 8. Recalibration ice data collection, using an agreed upon restricted but operationally relevant set of distances, viewing angles, and ice thicknesses, proceeded during the first half of the month, with ice ball testing occurring during the later part of the month. Following priority recalibration and supplemental ice ball test completion, it was planned that the unit would be shipped to KSC to support the STS-117 launch initially scheduled for March 15th and later June 8, 2007.

Phase 2 data collection and testing followed recalibration software uploading in late February, with the purpose of verifying ice camera accuracy. However, the system was again found *not* to be sufficiently accurate over the set of agreed upon operating parameters. Concurrently, a major rain and hailstorm occurred at KSC, causing major damage to the upper portions and surfaces of the ET SOFI. In fact, an estimated 4,500 hail hits were recorded with significant damage to SOFI found through inspection. As a result, the STS-117 launch was delayed indefinitely until repairs could be made or the tank replaced. This delay afforded a new and hopefully final recalibration algorithm to be developed and loaded into the ice camera. The new recalibration algorithm developed by MDA was based on ice density of 30-40 lb/ft^3 (normalized to 35 lb/ft^3), ice thickness of 0.040 to 0.080 in. (centered around the LCC of 0.0625 in.), a distance of 50 feet, and viewing angle of 80 degrees. However, shortly after the testing began the strobe failed and a decision was made in late March to send the unit back to MDA-Canada for inspection and repair, with subsequent return of the unit to Selfridge one month later.

Phase 3 testing to verify recalibration accuracy occurred over a brief one week period in late May with collected data indicating the system was very consistent with Kaman measurements. Finally, the ice camera could be verified as being in calibration and operationally ready. Based on the success of this last recalibration algorithm by MDA-Canada and the accuracy of test results achieved at Selfridge, it was decided to ship the unit to KSC for support of T-3 hour inspections for the STS-117 mission scheduled for June 8, 2007.

After shipment and receipt of the system at KSC, a NASA/TARDEC test team conducted a series of tests to verify that no damage had been experienced in shipment. The system was found to be accurate in its reading of varied ice thicknesses from a distance of 50 ft. and a viewing angle of 80 degrees. The system was declared operationally ready for launch support by TARDEC, MDA, and NASA during a joint telecon on June 5, 2007. The unit was used for T-3 hour inspections, but problems with the unit occurred during use. (More later on problems encountered.)

The ice camera was again returned to MDA in late June 2007 for inspection and necessary repairs. It was found that a high voltage cable and connector was burned, which would cause the IR strobe to stop working. The cable and connector were repaired and the LCD panel replaced. The unit was returned to KSC on July 24, 2007 to be tested and made ready for use during STS-118 T-3 hour inspections. This time the ice camera worked fine during inspections prior to the August 8, 2007 successful launch of Endeavor, however, because of a high pad temperatures and heat index exceeding 109°F virtually no ice was visually present or indicated by the ice camera.

Dates	2007 Milestones
1/26/07	Ice camera received at Selfridge from KSC for next testing period, and hanger preparations made by TARDEC test team during the earlier week.
1/31/07	Bob Speece of NASA briefed the Level 2 Board on MDA STS-116 performance, planned future Selfridge testing. There was a positive response to the presentation and ice camera use to support STS-117 and no negative comments or concerns.
2/3/07	Supplemental funds transferred from NASA-KSC to TARDEC via MIPR.
2/5/07	Thick ice shell ball molds, Kaman, and the ice ball 12 in. x 12 in. Dewar were received from KSC.
2/5-9/07	Phase 1 Selfridge MDA ice panel data collection begins for first MDA recalibration. During this week all NASA provided test panels and

	equipment arrived.
2/12-16/07	Second week of data collection for MDA recalibration with some system problems and data dropouts. Ice thickness and thick shell ice ball testing conducted.
2/20/07	Agreement to proceed with testing and additional funding provided to TARDEC by NASA-KSC.
2/23/07	Ice camera recalibrated using Dr. Gregoris (MDA) provided application program.
2/26-3/3/07	Phase 2 data collected of ice thickness reading began to verify MDA recalibration. Thick shell ice ball testing completed.
2/26/07	Hailstorm at KSC caused major damage to ET. A decision was made not to ship the MDA to KSC in early March as planned, but to perform additional ice ball testing at Selfridge.
2/27-28/07	New calibration algorithm loaded and ice thickness data collection begun.
3/5-9/07	Period of data analysis and no testing at Selfridge.
3/12-4/6/07	Resumption of Selfridge Phase 2 testing and acreage ice and ice ball data collection.
3/27-4/25/07	Ice camera shipped from Selfridge to MDA-Canada for repair.
4/26/07	MDA unit returned to Selfridge for testing. However, the strobe was not working.
5/10-11/07	System again shipped from Selfridge/TARDEC to MDA-Canada for repair.
5/18/07	System returned to Selfridge from MDA-Canada.
5/21-25/07	Phase 3 of third test period at Selfridge for calibration verification and thin shell ice ball data collection.
5/29-30/07	System shipped to NASA-KSC and received.
5/30-6/1/07	MDA post-shipment testing and system readiness verification at KSC.
6/5/07	The modified, recalibrated system was declared ready for operational use by TARDEC, MDA, and NASA to support the STS-117 launch.
6/8/07	Ice camera used during STS-117, T-3 hour inspections followed by at successful vehicle launch. However, MDA inspection data was not recorded because of a VHS tape jam and other unanticipated system problems. There was visual detection of several frost balls on upper portion of ET but no ice on ET.
6/11-12/07	Post-launch inspection of the MDA unit could not identify the cause of the MDA malfunction except for the VHS tape jamming.
6/29/07	Ice camera shipped via TARDEC and received at MDA-Canada for inspection and repair.
7/24-31/07	The MDA system was returned to KSC for calibration reverification in preparation for use for STS-118 inspections.
8/8/07	System successfully used for STS-118 T-3 hour inspections.

Table 5. System Recalibration and Testing

e. Acreage ice calibration methods, results, and analyses

For this section on acreage ET SOFI ice and ice ball testing, test results presented in the following charts are considered representative and sufficient for a summary and final assessment of the prototype ice camera tested during 2007 at Selfridge. It is not felt that there would be any advantage in including and presenting analysis for *all* test days and *all* measurements. The total test

data set from all test periods are on file and available from Dr. Thomas Meitzler, VPL leader of TARDEC. For ice camera maintenance records for this 2007 test and other periods see Appendix 3.

Methods–Ice formations for this 2007 test period were basically the same as was used for 2006 Selfridge testing. By joint agreement between NASA, TARDEC, and MDA, test data sets were limited to a viewing angle of 80 degrees, a distance of 50 ft., with ice thicknesses of 0.040, 0.050, 0.060, 0.070, 0.080, and 0.100 in. Time permitting ice of 0.250 in. was to be created and data collected. However, data collection and calibration was to focus on the LCC thickness of 0.0625 in. A new “Lazy Susan” was constructed by TARDEC with an 80 degree viewing angle capability, and revised procedures were developed for Selfridge recalibration, ice formation, and data collection.

New milled and thinner SOFI test panels provided by NASA-KSC and received at Selfridge would make ice formation faster and easier to control. However, they were found to have too many pits caused by the milling process to be useful. As a result, a joint decision was made to use the same milled SOFI panel that was used during 2006 testing. This decision was important because then only a single ice target panel would be used for ice camera testing and at least one test variable would remain constant.

Figure 14 is a picture of the 2007 (and 2006) Selfridge hangar test setup, showing the relationship between the MDA unit and the cryogen test panel. The MDA unit is in the foreground with the test target ice panel in the background with a team member standing in front of the panel.

Figure 14. Image of the test setup in the Selfridge hangar

Figure 15 is another view of the MDA cart-mounted system with an open front panel. Figure 16 shows the ice covered SOFI sample with fish line grid references mounted on the CTC, a LN2 supply Dewar, and supporting test equipment including the Wagner paint sprayer that was used for controlled ice creation. Additional test panel pictures and information are contained in Appendix 6.

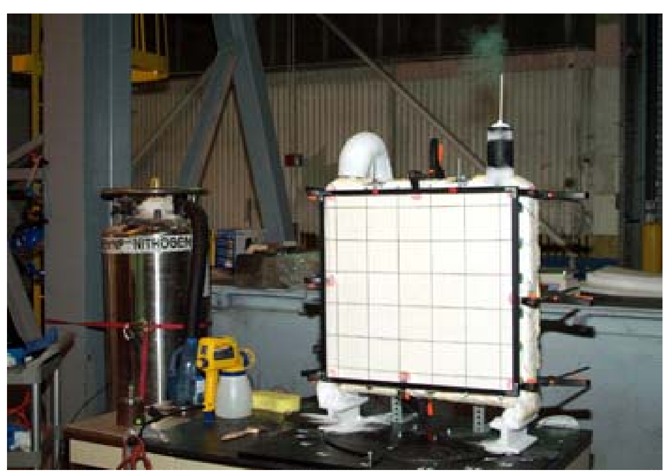


Figure 15. Ice Camera ET Inspection System Cart

Figure 16. Supply Dewar, ice covered SOFI target ice with a Kaman measurement grid, and Wagner water sprayer

Results–During much of the 2007 test period, the ice camera is considered to be "out of calibration" when compared to what were considered reasonable differences between remotely sensed MDA and Kaman measured ice thicknesses. Ice camera readings were consistently 10 to 15% higher than Kaman thickness measurements. A special test was run with the ice camera focused on a fixed ice thickness for 20 minutes. During this data collection period only a 2% change in contrast values (ice thickness) was noted. This was an indication that the ice camera *could* be calibrated if the right balance between operating parameters and algorithm was found.

When it became evident to Dr. Meitzler and the group that this prototype system probably would not be capable of being calibrated for a full set of viewing angles, distances, and ice thicknesses, a key decision was jointly made by NASA, MDA and TARDEC to limit expectations to a more reasonable range and set of operational parameters. It was agreed that data was to be limited to a maximum distance of 50 ft., a viewing angle of 80 degrees, and ice up to the LCC of 0.0625 in. Ice thickness beyond the LCC and up to the originally planned 0.250 in. were not important to NASA because if formed ice reached the LCC thickness, a "no go" for launch condition would exist if the ice was in a "critical for flight" area on the ET. Further, test ice densities from 30-40 lb/ft^3 were targeted because according to NASA (Stevenson and Speece) this range was the nominal density of KSC ice. This decision eventually resulted in the calibration of a system that was acceptable to NASA for pre-launch inspection operations.

During testing, test panel ice was developed using the original 2006 test panel to produce ice of the desired density. At least five runs were made to produce data sets at a viewing angle of 80 degrees, and distance of 50 ft. with ice around the LCC of 0.0625 in. (along with other thicknesses). While it was difficult to control test ice density because of hangar and ambient temperatures ranging from 20 to 50°F, every effort was made to form ice within the nominal KSC density range of 30-40 lb/ft^3 with an ideal density being 35 lb/ft^3. The data show that ice density *decreased* as ice got thicker.

For a complete list of required test equipment see Appendix 7.

Analysis–The above density change, indicated from the data, is important for understanding and future testing. But test ice creation is a very complex and not a fully understood process. For example, it has been observed by Selfridge test personnel that ice densities at the end of the test day (when test panels are routinely measured) were lower than ice densities formed at the start of test day. There are several theories as to why ice density varies throughout testing. One is because of the way test ice is layered. Later added ice is probably of lower density than earlier underlying ice, and as a result helps to raise the average density of the layered ice. Another theory is based on the method in which ice is created. Initial test ice on a test SOFI panel is achieved in several fairly close (in time) sprays. Therefore, there can be greater control over when ice is sprayed, how wet or frosty

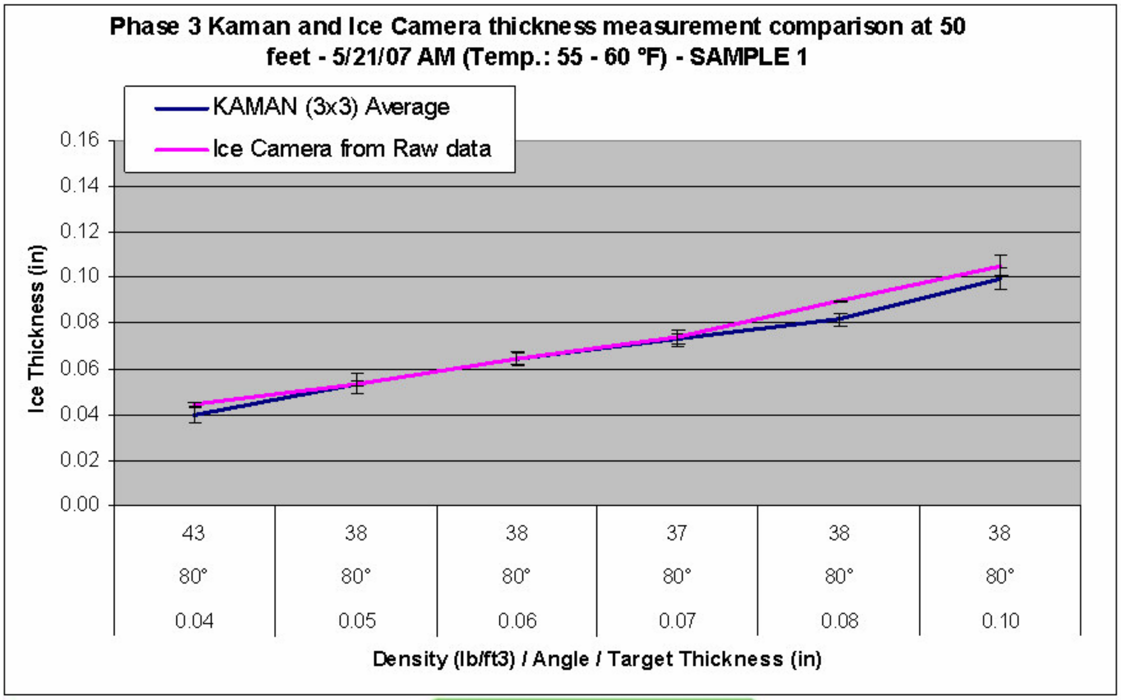
it is, and how long spraying occurs, which can cause more or less melting as desired. Higher density ice can result when melting occurs during spraying. After first ice is created, additional thicknesses of ice are only 0.010 in. thick. This is achieved in only a single ten second spray. Longer sprays can induce higher temperatures, thereby melting base ice, which results in higher densities. Spray can also be performed from a closer distance to deliver warmer or hot water, but this can cause other problems like uneven ice thickness. Also, subsequent sprays are done after measurements, thereby giving the ice time to chill down, making it even more difficult to raise the temperature of ice above freezing with only a ten second spray. And during the pause for measurements ice bumps can grow, potentially also reducing density. So as can be seen, test ice creation is both a science and an art. While this testing has resulted in a better understanding of test ice creation, there is much more to be learned.

It should be noted that it has been calculated by Darryl Bryk of TARDEC, using early 2007 Selfridge data, that there is a relationship that exists between the uncertainty of ice density and ice thickness. As that data and statistical calculation indicated in Appendix 12, there is an *inverse* relationship between the uncertainty of ice density and ice thickness for Selfridge test ice for a range of 0.040 in. to 0.250 in. ice thicknesses. Within this range of values as ice thickness goes up, ice density decreases. The implications of these calculations and best estimate determination are yet to be fully reconciled.

Regardless of the uncertainties of ice layering, creation, and thickness and density inter-relationships, as data were collected during various phases of testing, Dr. Gregoris of MDA developed revised MDA operating calibration curves within agreed upon operating parameters. Following his periodic revisions the revised curve was compiled with results provided via FTP to Selfridge test personnel for uploading into the ice camera unit. This iterative process continued until the ice camera was found to be “in calibration” and validated for KSC operational use.

During the 2007 period at Selfridge, testing for the purpose of improving the accuracy of ice camera ice thickness (around the LCC value of 0.0625 in.) was the focus of data collection. The best way to describe the results of Selfridge testing from early February to late May 2007 is to say that data were collected, and calibration algorithms developed and loaded into the system in successive approximations. Finally, during phase 3 testing, the system was found to have reached an acceptable accuracy level when MDA remote reading compared favorably and to an acceptable level with Kaman physical ice thickness measurement.

A great deal of data exists for 2007 acreage ice testing, but the following plotted data for an *80 degree* viewing angle are representative of Phase 3 results. As the following chart indicates, there was close association between MDA ice remote readings and Kaman measurement for ice thickness levels ranging from 0.040 to 0.070 in. for ice between nominal densities of 30-40 lb/ft^3. Variation occurs for densities outside those limits and ice thickness in exceed of 0.070 in. Because of repeated and consistent data, the system was considered calibrated and validated for STS-117 use at that time. In fact, data show that with proper calibration, the ice camera accuracy achieved is within ±0.010 in. The development of a revised calibration parameter by ice camera system designer Dr. Dennis Gregoris of MDA proved that the system could be calibrated to an accuracy needed by NASA.



It should be realized, however, that ice camera calibration was achieved with a reduced but acceptable set of operational parameters (i.e. a viewing angle of 80 degree, from 25 to 50 ft., and for ice thickness up to an slightly higher than the LCC ice thickness of 0.0625 in.). As was indicated from test data and analysis, care must be exercised for ice thickness reading above 0.070 in. The test team had been successful because instead of trying to calibrate the system for all possible viewing angles (e.g., 90 to 20 degrees), distances (e.g., 25 to 100 ft.), and ice thicknesses (e.g., 0.050 to .010 in.), a more reasonable set of values and limits were targeted.

By understanding the calibrated limits of the system, a T-3 hour inspection operator can position the unit on a platform in such a way that ice presence and thickness readings, within the range of achieved accuracies, can be believed for ice thickness information and LCC "go" or "no go" decision purposes.

f. Thick shell ice ball methods, result, and analysis

Methods–Thick shell ice balls of 1, 2, and 3 in. hemispheres were part of phase 1 February 2006 testing. This type of ice ball is defined by NASA as being a hemisphere shape with a wall thickness of 0.40 in. maximum with a frost center. These balls have a thicker base like a donut, and an overall density of 47 lb/ft^3. Test ice balls were not made solid because their density would be too high and not representative of actual ice balls formed on ET SOFI. A method of test ball development suggested by TARDEC (Greg Smith) used available Selfridge snow as core frost. It was also clarified by NASA (Charles Stevenson) that, almost without exception, ice balls form on as-sprayed SOFI and not acreage ice already formed.

However, it was realized that it would be difficult if not impossible to grow or "glue" ice balls on bare SOFI in a test setting. Therefore, it was agreed that test ice balls would be adhered to the thinnest SOFI ice possible. For formal testing, an ice foundation of 0.020 inch was made on the SOFI sample panel. The ice was sanded significantly in an attempt to make the ice camera indicate a solid green color. Three hemispheric formed balls of 1, 2, and 3 in. in diameter were carefully

removed from their female mold cavities, and then "glued" onto the vertical 2 ft. x 2 ft. test ice panel using water. The best technique for mounting the ice ball samples was to use the Wagner airbrush sprayer to wet the back of the sample, and stick them onto the foundation ice.

Results–Secondary testing priority, thick ice ball formation and detection, used an agreed upon formation and test set up procedure. Thick ice balls were created using a KSC-developed and supplied half mold lying on a horizontal 2 ft. x 2 ft. Dewar. Water was sprayed into the female mold to form shells of various diameters, i.e. 1, 2 and 3 in. diameters, and packed with Selfridge snow to form frost centers. See Figure 17.

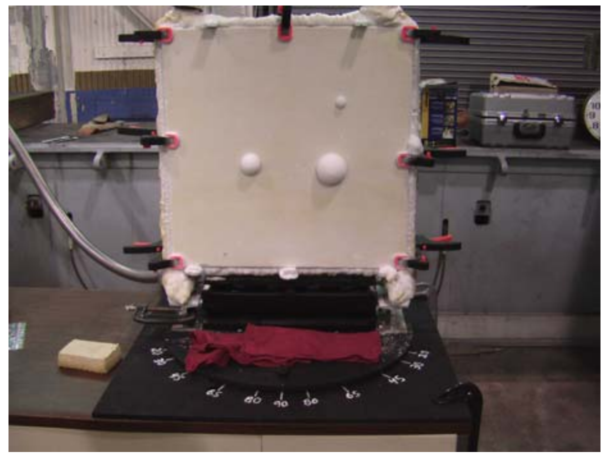


Figure 17. Test panel with 1, 2 and 3 in. diameters ice balls.

For one test, the thick shell ice balls had the following densities: 1 in. diameter–52 lbs/ft^3, 2 in. diameter–54 lbs/ft^3, and 3 in. diameter–41 lbs/ft^3. Most of the ice balls made were 39 to 41 lbs/ft^3, but balls were not chosen based on density. See Appendix 10 for additional information on thick shell ice ball creation and procedural steps.

Analysis–The MDA camera is able to detect 3-in. ice balls as far as 40 ft. away at viewing angles of 90 and 45 degrees. The system also sees 2-in. hemispheres at 25 ft. or less. Satisfactory results were not found for one in. balls, which were difficult to see at most distances and angles.

g. Thin shell ice ball methods, result, and analysis

Methods–Thin shell tests were planned for phase 3, with the focus on determining the capability and limits (i.e. distances, viewing angles) of the ice camera with concentration on 2 and 3 in. diameter thin shell ice balls. This type of ice ball is defined by NASA as having a wall thickness of 1/8 to 1/10 in. with frost inside. Like thick shell balls, they are donut shaped at their base where they are attached and form on ET SOFI. They typically are 27 lb/ft^3 in overall density. Testing was to take place at 60 ft. or greater and at viewing angles less than 65 degrees. Empty and solid thin shell ice balls were included in this testing, because of the difficulty in forming "ideal" thin shell test balls (thin shell with a frost center) and the lack of experience in creating them.

The challenge was to create simulated ET thin shell ice balls consisting of a thin ice coating over a frost center. Thin shell molds having female and male half sections were fabricated at KSC and shipped to Selfridge. Visible in Figure 18 is a 12 in. x 12 in. Dewar on its back, with ice ball molds on top. Procedures were developed for ice ball creation and data collection, as was a Selfridge *Ice Ball Test Plan* dated 5/1/07 developed by NASA (Thomas Moss). (Reference Appendix 11 for the thin shell ice ball development procedure.)

Figure 18. Horizontal Dewar and ice molds

Selfridge thin ice ball testing consisted of creating and detection/measurement of: a) empty thin balls, b) thin shell ice balls containing frost, and c) higher density packed ice

shells. NASA (Charles Stevenson) indicated that priority should first be given to testing frost filled ice balls, second empty thin ice shells, and last solid (high density) ice balls. Ideal thin shell balls, that best represent KSC conditions, would consist of frosty hard shells with a frost inside.

Results–The thin shelled test ice balls constructed during this phase of testing were similar to those formed on actual SOFI–thin shells with a frost center. This is a significant advancement in that it provides a detection capability for the NASA ice ball LCC. One test ice ball was found to have a density of 48 lb/ft^3, which was very close to the ideal density of 47 lb/ft^3 identified by NASA (Charles Stevenson). In general, the ice camera detected ice balls of the following sizes and distances: 3-in. diameter balls at 60 ft., 2-in. balls at 50 ft., and 1-in. at 25 ft. See Figures 19 and 20.

Figure 19. Thin shell ice balls of 2 in. (in red) and 3 in. diameters (in blue) detected at 40 ft. and 90 degrees (left)

Figure 20. Thin shell ice balls of 2 in. (in red) and 3 in. diameters (in blue) detected at 25 ft. and 90 degrees (right)

Analysis–Ice ball data portrayed on the ice camera display indicated that the system is able to detect balls of 2 and 3 in. diameters from distances from 25 to 50 ft. primarily from viewing angles of 90 (normal) and 45 degrees. Some detection of 3 in. diameter ball was possible up to 100 ft. from a normal (90 degree) viewing angle. However, ice balls of 1 in. in diameter at any distance are almost impossible for the ice camera to see beyond 25 ft. Ice balls less than 2 ft. are, fortunately, not part of the ice ball LCC.

Another way of analyzing ice ball detection is through the following form of chart as is represented in Figure 21 below. While not exact for analysis purposes, it is a summary way of indicating that the ice camera can detect ice balls of various sizes and internal content. Figure 21 displays ice camera data in a histogram format that indicates detection capability in the form of pixel color counts. These color bars represent some of the ice camera's interpretation and count of ice ball shell thickness and composition.

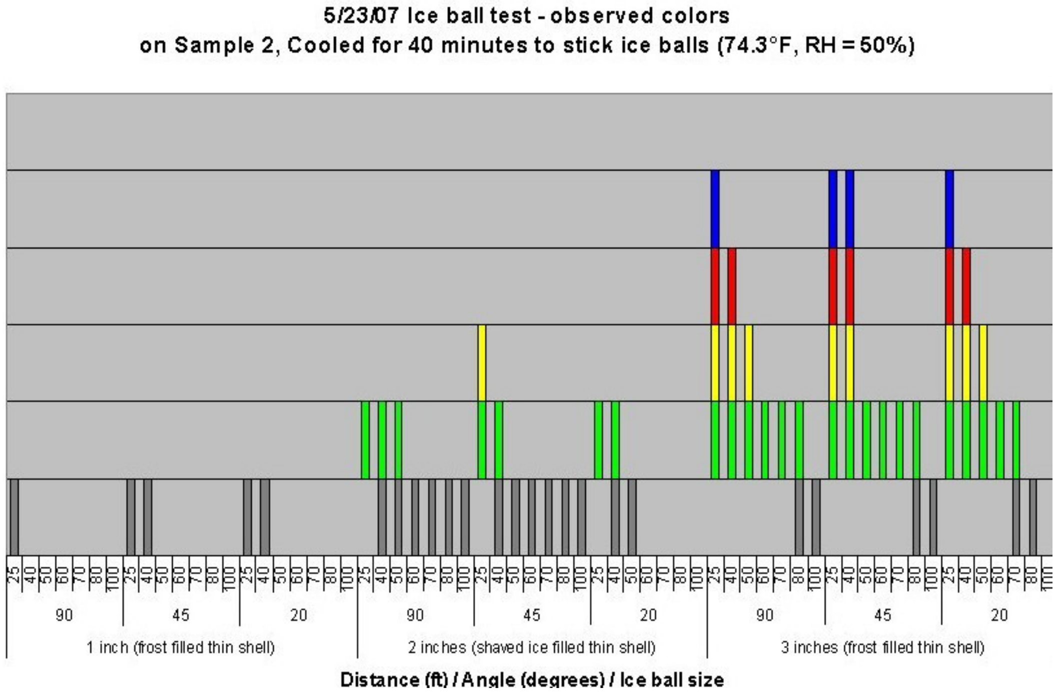


Figure 21: MDA thin shell ice ball detection data representation.

Test viewing angles were 90, 45, and 20 degrees, and viewing distances were 25, 40, 50, 60, 70, 80 and 100 ft. Test thin shell ice balls formed in the male and female mold halves were filled with frost and shaved ice. While the following interpretations are in no way exact or quantitative, some conclusions that support MDA displays can be drawn. Three inch diameter thin shell ice balls are visible from 25 to 50 ft. at most test viewing angles (i.e. 90, 45, and 20 degrees), with some detection beyond 50 ft. but primarily from 90 and 45 degree viewing angles. Two inch diameter ice balls are visible between 25 and 40 ft. for most test viewing angles, but not beyond. One inch diameter ice balls are not visible beyond a distance of 25 ft. However, these interpretations must be used with caution, because the MDA pixel count representations indicate some ice thickness readings that are not fully understood at this time or correlated for ice hemispheres and not typical SOFI ice surfaces. The calculation of the number of pixels on a one-in. target is included in Appendix 2. Also included in this appendix are figures showing bulls-eye size versus range, and the number of pixels horizontally on a 2 ft. x 2 ft. SOFI test panel by viewing angle.

In spite of the lack of an understanding of MDA color reading for thin shell ice balls at this time, NASA (Stevenson and Speece) is very pleased with the results of ice ball testing conducted at Selfridge. It is clear that the ice camera has the potential to detect 3 and 2 in. ice balls at nominal KSC inspection distances (25 to 50 ft.) and viewing angles (90 to 45 degrees) and can support ice ball LCC decision making during winter launch periods. However, it is realized that thick and thin ice shell thickness accuracy determination will require further investigation, testing, and analysis.

STS-117 and STS-118 T-3 Hour Inspection Use and Results

Prior to the start of the STS-117 T-3 hour inspection on the pad, the MDA unit was taken to the pad by the seven-person team in a van. In the meantime, Bob Speece of NASA and others were monitoring the inspection remotely in the Launch Control Center (LCC) "Ice Castle." See Figure 22. Also in the LCC were two members of the TARDEC test team.

Figure 22. Bob Speece in the LCC "Ice Castle" monitoring T-3 hour inspections

Unfortunately, during inspections by NASA's Scott Lockwood, the unit's VHS tape jammed, and operator ice contrast and ice thickness displays showed only error messages. Also, late in the inspection process the ice camera would not boot, the strobe would not flash, and visual images of target areas could not be seen. It should be noted that the ice camera is a stand-alone system with only VHS tape data recording and visual displays, and no remote data recording. See Figure 23 for a picture of the MDA unit (on the right) during MLP setup.

Figure 23. Ice camera (on right) being used on the MLP during STS-117 inspections

During a post-launch inspection at KSC it was determined that no sensor data had been recorded to the unit's computer hard drive. The reasons for these system failures were not immediately understood, and a joint decision was made to send the unit back to MDA-Canada for inspection and analysis to determine the causes of these frustrating failures. One suspected problem was the high temperatures the unit experienced while being stored in a transport van while waiting for inspection team transfer to the pad. Temperatures greater than 100°F were estimated in the van, and high 80-low 90°F temperatures were recorded during inspection use on the launch pad. This unit had never been tested or used at the elevated Florida summer temperatures of launch day. NASA will procedurally prevent the system from remaining in a closed van during summer months prior to use.

Inspection of the ice camera, after return to MDA-Canada following the July 2007 STS-117 launch, revealed the primary cause of the system not booting up, the flash lamp (strobe) not firing, and the operator displays not working. It was found that a connector and associated wiring was burned, which explained why the strobe and displays would not work. There have been problems with this connector and wiring before because of the high current they carry. As a result both tend to fail after prolonged system use, which occurred as the result of extensive Selfridge testing and KSC post-shipment calibration validation testing. This design element will need to be improved.

By agreement MDA did the following to return the system to an operationally ready state for STS-118 launch support. Replaced were: a) the burned connector with an improved version, b) burnt wiring, and c) a non-critical failed interlock switch. In addition, the following agreed upon modifications have been made: the LCD operator display was replaced with a newer and improved version, and a software change was made to create a batch, back-up data file and prevent data from being lost occasionally when the system is stopped and restarted. It was planned that the VCR tape unit would not be replaced with a DVR for the launch of STS-118 but later. With the above repairs and system modifications, it was anticipated that the ice camera would be far more reliable for

future testing and operational use. The ice camera was tested by MDA in Canada before being returned to KSC to support the STS-118 launch scheduled for early August 2007.

After return to KSC, NASA and TARDEC personnel revalidated ice camera calibration (which should not and did not change) using a CTC and sample SOFI. In use during STS-118 T-3 hour inspections, the only problem was a broken pan-tilt locking lever used for ice camera head positioning, and a cracked glass on a purge gage. With these exceptions the system worked well including the tape system used to collect data. However, because of the high temperatures during the August 8, 2007 inspections, no acreage ice or ice balls were visually observed or detected by the ice camera. However, ice build up, was observed on the O2 feed line bracket and on a flange near the bottom of the ET, which is not unusual. See the Figures 17-1, 17-2, and 17-3 in Appendix 17 for pictures of the ice camera being used during the STS-118 launch.

When used operationally again in support of future pre-launch inspections, it must be remembered that this prototype ice camera use should be managed with some care. LCC quantitative ice thickness determination should be limited to 90 to 65 degree viewing angles, and distances of 25 to 50 ft. for anticipated KSC ice densities in the ranges of 30 to 40 lb/ft^3. The same is true for the detection of LCC ice balls on bare SOFI. In addition, because of the system's IR light source, use is limited to greater than 25 ft. from the vehicle, and operators should not look directly into the flashing strobe. Otherwise the system is safe to use and operators should not have any problem in differentiating ice from water, or locating ice on structural brackets, engine vents lines, or in other locations.

C. Overall Results and Accomplishments

1. Ice/frost detection

It was found early (2005) that the system cannot differentiate between ice and frost—frost defined by NASA as ice having a density of 18 lb/ft^3 or less. Initial testing indicated that naturally forming frost affects ice thickness measurement, and even when packed and having some thickness, frost appears much thinner than it actually is. Very thin frost has little effect on ice camera reading, but thicker layers of frost reduce ice thickness readings. If thick enough, frost appears to be low density ice. Under test conditions favorable for natural frost growth, frost can grow thick enough to obscure underlying ice. In fact, the ice camera cannot see or measure ice under frost that is more than 1/4 in. thick. But from a system requirement or operational reality standpoint, frost is not an STS problem or LCC consideration because it does not form with any thickness that is a launch constraint. What is a problem is when frost densifies into ice as a function of time, temperature, and relative humidity.

2. Ice/water differentiation

Early testing (2004 and 2005) proved conclusively that the ice camera could clearly differentiate between clear water and clear ice. Water is displayed as black and ice as a color in the ice camera display. This is a significant capability, because to the human eye at a distance, cold water and clear ice are very similar and almost impossible to distinguish between. Water, in the form of condensate, is not a pre-launch constraint on SOFI, unless it freezes and exceeds the 0.0625 in. LCC. Fortunately, the MDA ice camera is an ice detection system that clearly differentiates ice from water.

3. Acreage ice thickness measurement

Accurate ice thickness determination for SOFI acreage ice was the most difficult ice camera capability to develop. Several years (2005, 2006, and 2007) and cycles of recursive ice formation, data collection, calibration, retesting, data collection, and recalibration were required to develop this ice camera capability. When NASA agreement was reached to limit viewing distances and angles to reasonable KSC operational limits, a successful calibration was found by MDA and TARDEC that improved system accuracy to a very acceptable level. These reasonable and nominal operational limits were: a) a viewing angle of 80 degrees, b) a viewing distance from 25 to 50 ft., and c) ice thicknesses up to and slightly higher than the LCC ice thickness of 0.0625 in. Also, ice density, which the MDA is sensitive to, were limited for the purpose of system calibration, to nominal KSC ice densities of 30 to 40 lb/ft^3 (normalized to 35 lb/ft^3). Under the above viewing angle, range of distances, and ice thickness limits, the system has been proved to be accurate, and more importantly, it does not overestimate ice thickness, i.e. indicate ice that is thicker than it actually is.

4. Ice ball detection and measurement

An LCC for thick and thin shelled ice balls was evolving as this project progressed, and was described to the TARDEC/MDA team by NASA. Ice balls were identified as hemispheres, having some thickness and either having an ice thickness of 0.40 in. maximum for thick balls, and 1/8 to 1/10 in. for thin shelled balls. Both are frost filled with varying densities. Testing of both types of balls was accomplished in 2007 with good results, but a limited understanding of the capability of the ice camera to determine ice shell thickness presently exists. From thick and thin shell ice ball test results, it is known that three inch diameter ice balls are visible from 25 to 50 ft. at most test viewing angles (i.e. 90, 45, and 20 degrees), two inch diameter ice balls are visible between 25 and 40 ft. for most test viewing angles, and one inch diameter ice balls are *not* visible beyond 25 feet. Based on LCC concerns for ice balls larger than 2.3 in., the ice camera should *not* have a problem in

detecting ice balls of LCC concern on SOFI up to 50-60 feet away. What is not understood yet is the capability of the ice camera to measure ice ball shell and frost content thicknesses. Complicating matters is the fact that ice balls are donut shaped at their interface with the SOFI they are attached to and grow from.

A method has not yet been found to *grow* test ice balls to bare SOFI as is normal during KSC pre-launch operations following ET cryogen loading. However, during 2007 testing a method was found to *attach* ice balls to bare SOFI. The method uses the flat side of an ice ball mold, which has been partially melted and held to the surface of the bare SOFI until it freezes and ice balls become attached.

5. Portability

Except for the weight and maneuverability problem, NASA is generally pleased with ice camera use around launch facility work platforms and access ramps. But the bulky nature of the present design and weight of approximately 200 lb. makes the system awkward to transport and maneuver. The basic weight and size constraints inherent to the system's design and operation are a battery, purged enclosures, a purge bottle, and an operator display and data recording system. The replacement of the VCR with a more reliable DVR will hopefully reduce system weight by a few pounds. The goal is that the operational system size and weight will be smaller and lighter and more operator friendly.

D. Summary, Conclusions, and Recommendations

1. Summary

The NASA-KSC/TARDEC Space Act Agreement (SAA) of 2004 opened the door for the exploration of future mutually beneficial organizational activities between agencies. A SOW signed the same year and renewed in 2006 led to the identification of a NASA critical need for a system that would remotely detect and measure acreage ice on ET SOFI. The formation of ice in the form of acreage ice on SOFI can occur because of Florida winter temperatures and condensation that forms on SOFI due to the extreme minus temperature levels of the cryogenic fuel (LH2) and oxidizer (LO2) loaded and stored during pre-launch operations. Although ice formation on SOFI is more of a problem during Florida winter months, frost-filled ice balls can form even in warm summer months, because of cracks and voids that may be present in SOFI.

Under the SAA and SOW of 2004, Dr. Meitzler and members of TARDEC's VPL performed a technology search and evaluation of potential electro-optical systems capable of remotely detecting the presence and determining the thickness of ice. Research indicated that of several technologies investigated including radar, surface acoustic waves, and ultrasound, it might be possible to detect and image ice-covered areas using IR-based technology.

After testing and evaluating three IR-based ice detection systems, TARDEC recommended to NASA that the concept and ice camera developed by MDA of Canada showed the greatest potential for meeting NASA's needs and requirements. The recommended system operates on the physical principle discovered by the inventor, Dr. Dennis Gregoris that there is a specific wavelength band over which the electromagnetic (EM) reflectance spectra of ice and water are significantly different. These bands are part of what is usually referred to as the near IR or short wave infrared (SWIR) portion of the EM spectrum, between 1.1 and 1.4 microns.

Testing of an MDA contracted and delivered proof-of-concept system took place in 2005. During February and March 2005 testing of the system verified the potential of the system for remote ice detection and measurement. The system was shipped to NASA-KSC for familiarization and human factor testing, with the target system delivery and first planned use being Space Shuttle *Discovery*'s return to flight scheduled for July 2005. The main reason for sending the unit to KSC was to perform fit and functional tests in launch complex elevators, and on access and work platforms. Ice camera components had been integrated earlier into a NASA approved and supplied cart and fitted with a gaseous nitrogen pressurization system to meet KSC launch pad safety requirements. The system was modified and upgraded for a new round of testing at the request of NASA. Electromagnetic emission tests were accomplished by MDA prior to delivery to TARDEC and found to fall within EMI/EMC requirements.

Subsequently, a contract was let to MDA to modify and deliver a prototype and improved ice camera to TARDEC in March 2006. A series of tests were performed in a Selfridge hangar to investigate the performance of the prototype system during March to mid-August 2006. These tests were intended to replicate various NASA-KSC parameters and conditions to which the system eventually would be required to meet. In general, it was found during most of the 2006 tests that MDA remote readings underestimated as well as overestimated ice thickness compared to actual measurements made with a NASA-provided Kaman instrument being used to measure actual ice thicknesses. This demonstrated that a risk existed in dependency on the MDA device for ice thickness reading during KSC pre-launch tanking and T-3 hour launch pad ice inspections. NASA was cautioned by TARDEC that ice camera ice thickness measurements be used with caution, and that other tools and the critical eyes and experience of human observers should be used in making "go-no go" launch decisions. It should be realized, however, that 2006 testing took place mostly during the summer, and that procedural control for ice formation and maintenance was difficult at times and undoubtedly resulted in some experimental noise and error.

The improved prototype ice camera evolved and became more accurate through recalibration using test data obtained by TARDEC and NASA during Selfridge testing in 2007. During early phases of this testing period, the system had some instability and inaccuracies in ice thickness readings, and was not linear over test distances and angles. During testing it was also found that ice thicknesses were considerably underestimated in comparison with actual physical measurements using a Kaman ice measurement device. Later, observations indicated that lower density ice measurements were also underestimated in comparison to higher density ice. In addition, during 2006 and 2007 Selfridge testing, the ice camera was found to be somewhat unstable with respect to component reliability. On several occasions, MDA personnel were called in because of system problems such as IR strobe unreliability and user display discoloration. Corrective modifications were taken to replace components, add extra insulation, and re-solder connections. The system software was upgraded several times to try to improve ice thickness accuracy. Regardless, this ice camera was a breakthrough in remote ice detection and measurement.

To date, the ice camera has been used to collect engineering data for three shuttle missions–a launch attempt and successful launch of STS-116 in December 2006, the launch of STS-117 in June 2007, and the launch of STS-118 in August 2007. The system did detect some acreage and other normal accumulations of vehicle ice during STS-116 inspections in several locations. However, in spite of successful pre-launch system calibration testing and verification at Selfridge and KSC, for reasons that were not anticipated, the system did not work properly for STS-117 launch inspections. For that reason, the system underwent repairs, and some modification at MDA-Canada. Calibration was verified before pre-launch inspections for the STS-118 mission at KSC and the system was

successfully used for the August 8, 2007 launch. While acreage ice was not present or detected because of high KSC pre-launch ambient temperature, data were collected and the system worked without problems or issues except for a broken head pan-tilt locking lever and cracked purge gauge glass face.

Without an ice detection and quantitative measurement system, there is an increased risk that undetected ice could be liberated during ascent and strike the thermal protective tiles or windshield of the orbiter resulting in severe damage to the orbiter and/or endangering the lives of astronauts on board during assent. The ice camera has the potential to provide another tool for use by the NASA ice debris inspection team to increase the safety of launches and also provide data to help determine if a launch is recommended in the cases of minimal amounts of ice. The financial penalty for a launch scrub is estimated to be millions of dollars. The cost of a Shuttle launch failure is incalculable.

2. Conclusions

Early testing in 2004 and 2005 proved conclusively that the ice camera could clearly differentiate between clear water and clear ice. This was a significant capability, because to the human eye at a distance, water and clear ice are very similar and almost impossible to distinguish between.

Accurate ice thickness determination for SOFI acreage ice was the most difficult ice camera capability to develop. Several years (2005, 2006, and 2007) and cycles of recursive ice formation, data collection, recalibration, and retesting were required to improve the system. When reasonable KSC operational limits were developed, a successful calibration was accomplished by MDA that improved ice camera accuracy to an acceptable level. These limits were a viewing angle of 80 degrees from normal to the SOFI surface, viewing distances from 25 to 50 ft., and ice thicknesses up to and slightly higher than the LCC ice thickness of 0.0625 in. Also, ice density, which the ice camera is sensitive to, were limited for the purpose of system calibration, to nominal KSC ice densities of 30 to 40 lb/ft^3 (normalized to 35 lb/ft^3). Under these reasonable and nominal viewing angle and distances the system had been proven by data analysis to be accurate to ±0.010 in., and more importantly, it does not overestimate ice thickness, i.e. indicate that ice is thicker than it actually is.

A NASA LCC for thick and thin shelled ice balls that evolved as the project progressed was identified to TARDEC/MDA during the 2006 testing period. Testing of both types of balls was accomplished in 2007 with good results, but with a limited understanding of the capability of the ice camera to determine ice shell *thickness*. From thick and thin shell ice ball test results, it is know that three inch diameter ice balls are visible from 25 to 50 ft. at most test viewing angles (i.e. 90, 45, and 20 degrees), two inch diameter ice balls are visible between 25 and 40 ft. for most test viewing angles, and one inch diameter ice balls are not visible beyond 25 feet. Based on LCC concern for ice balls larger than 2.3 in., the ice camera should not have a problem in detecting ice balls of concern on SOFI. What is not understood yet is the capability of the system to measure ice ball shell and content frost thicknesses. Complicating matters is the fact that ice balls are donut shaped at their interface with the SOFI ice they are attached to and grow from.

It is now known that the MDA ice camera system can detect the presence of ice formed and can measure the thickness of the ice on the SOFI surface covering the ET of the Space Shuttle. Using a 60W near infrared strobe, it can also discriminate between cold water and ice, and detect thick and thin shell ice balls, which a trained operator can estimate in size from the system screen display. From ice camera operations, inspection team members can determine if SOFI acreage ice exceeds

the LCC of 0.0625 in., or if ice balls with diameters of 2.3 inches or greater exist on bare SOFI. Both violations could be the basis of a STS launch being postponed.

A general conclusion resulting from this combined TARDEC/NASA testing is that the present modified prototype ice camera, when repaired and its calibration revalidated, will be ready for "prime time" and the next series of STS launches until an operational system is built and available. The ice camera, with its present level of calibration can be used as an LCC (0.0625 in. ice thickness) detection system based on its color displays (e.g., green is good, yellow is caution, and red, blue, or magenta indicates unacceptable ice), and as a *quantitative* tool for ice measurements. However, for operational use, extreme care is needed in using ice thickness values indicated by this system if certain operational parameters are exceeded. Its use should be limited to 90 to 65 degree viewing (incident) angles, and distances of 25 and to 50 ft. Care should also be taken in believing ice thickness readings of this prototype system for ice > 40 lb/ft^3 (likely for very thick ice in various engine and bracket locations) and ice under frost which is not a normal KSC condition. Also, because of the system's IR light source, use is limited to greater than 25 ft. from the vehicle, and operators should not look directly into the flashing strobe.

Except for the weight and maneuverability problem, NASA is generally pleased with the potential of the MDA concept and ice camera for movement to and around launch facility work platforms and access ramps. But the bulky nature of the present design and weight of more than 200 lbs. makes the system awkward to maneuver. The basic weight and size then drives the system design and operation are a battery, purged enclosures, a purge bottle, and an operator display and data recording system. In time with the replacement of the VHS recorder and with the installation of a more reliable DVR recorder, some few pounds will be saved. The hope is that the operational system size and weight will be lighter and more operator-friendly.

The best encouragement and endorsement of this development effort was, after Charles Stevenson of NASA reviewed Selfridge test data, was his statement that "the SAA team has developed an ice detection and measurement system in less than three years, that has the potential to solve a problem that NASA has struggled with for more than 25 years–SOFI acreage ice detection and measurement, and more recently ice ball detection."

The following table summarizes the operational performance capabilities of the prototype MDA ice camera system that have been achieved from reiterative development testing at TARDEC, Selfridge, and KSC, and field human factor studies and operational use during three KSC STS pre-launch inspections of acreage ice and bracket and vent ice when it existed. The term measurement is used here to indicate the reading displayed on the ice camera operator panel.

Operational Parameters	Capabilities
Operational viewing range	25 to 50 ft. (with some detection of ice at 100 ft.) Note: the system should not be used within 25 ft. of the vehicle.
Illumination	Full sunlight to total darkness
Ice thickness measurement range	0.020 in. to 0.250 in.
Calibrated measurement range	0.020 in. to 0.080 in.
Accuracy of readings within calibrated measurement range	±0.010 in.

Ice detection viewing angles (from normal to the SOFI surface)	90 to 20 degrees
Operational ice measurement viewing angle limits	90 to 65 degrees
Ice ball detection (thick and thin) within the operational viewing range and viewing angles	Three in. diameter balls between 25ft. and 50 ft from angles of 90 to 20 degrees. Two in. diameter balls between 25 and 40 ft. from most viewing angles. One in. balls not visible beyond 25 ft.
Ice under frost	Reduced ice thickness reading under very thin frost (0.010 in.), and no reading with frost > 1/4 in.
Eye protection	Operators should not look directly into the flashing strobe
Operational system use time	> 2 hours
System weight	Approx. 200 lb.

Table 6. Summary Prototype MDA Ice Camera Operational Parameters and Capabilities

3. Recommendations

Several recommendations are advanced for consideration. First, based on what has been learned to date, that a new round of testing be initiated by TARDEC/NASA at Selfridge when the ice camera is available between STS launches. The focus of this investigation would be on improving thicker ice measurement accuracy above the LCC of 0.0625 in. at KSC nominal density ice up to 0.250 in. with more data collection, and more extensive ice ball testing to expand shell thickness evaluations and content measurement understanding. More needs to be done to better understand how the ice camera performance changes as ice "ages." That is, how does test ice density change as a function of thickness growth. It would be advantageous if this testing occurred prior to the planned December 2007 launch of STS-120 when ice balls have a potential for forming on ET SOFI in the cold Florida "winter" air. There may also be a test methodology justification for using liquid helium as the cryogen to assist in the formation of test ice balls, as was used during earlier NASA Stennis Space Center testing to develop an ice ball LCC. However, it is realized that the use of helium may be cost prohibitive. If possible it is better to test at Selfridge during the colder winter period (November through April) when ice density is easier to control and test for density variation, and ice forms more quickly for ice ball attachment. It is also suggested that in the future, an enclosure around the test SOFI and Dewar (8 ft. x 10 ft. or greater) should be constructed with air conditioning to help control and maintain ice thickness and density within the Selfridge hangar and KSC test facility.

Second, as changes are made to the existing MDA prototype ice camera to improve its functionality, reliability, and accuracy, more extensive testing and calibration verification at Selfridge may be needed for future NASA-KSC launch processing inspections. It is now recognized that the present system, which has evolved from a concept model made from off-the-shelf components, lacked the reliability needed during extended testing and KSC operational transportation and use during pre-launch inspections. Additional Selfridge testing to verify the system's functionality, reliability, and accuracy would not be a wasted effort, because it is planned that the present ice camera will serve as a backup system for KSC inspections even after a

replacement and next-generation operational system is available–perhaps not for more than one year. But not all testing would occur at Selfridge. The more frequently the system is used at KSC for in-field mobility/human factor/engineering testing and operational use, the more data can be collected for analysis, and the sooner improvements to the present system can be made. Also, data and analysis from any testing at Selfridge and field evaluations at KSC would greatly benefit the design and development of an operational system.

Third, as suggested by Dr. Meitzler to Mr. Charles Stevenson, consideration should be made by NASA to make available dedicated land lines on launch pad structures (i.e. Fixed Service Structure and Rotating Service Structure) for ice camera connections at various selected levels. For inspections, the ice camera could then be connected at various points on the structures for data distribution to and display in the LCC “Ice Castle.” This data redistribution, would serve to aid the real-time decision making process for ET SOFI acreage ice and ice ball LCC violation determination. In addition, data recording in the LCC would serve as a backup to internally recorded ice camera data. However, to make these displays and recordings possible, the ice camera would have to be modified by MDA to put a cable output on the camera that is compatible with data cable connectors on the launch pad structures.

Finally, NASA should fund as soon as possible, and participate with TARDEC and MDA, in the design, development, and testing of an operational ice detection and measurement system that is customized for KSC STS ET acreage ice, ice ball, and ice formations on brackets, vents, and other cold surfaces. The sooner new funding is made available the better, because it is estimated that an operational system will require twelve months for development, construction, and verification testing. In the meantime during Florida’s winter launch periods, the present prototype and eventual operational system should be invaluable for remaining STS flights in detecting and accurately determining the presence and thickness of ice on ET SOFI and the presence of ice balls. Also, there is every reason to believe that any developed ice camera would be useful for checking ice formations on cryogen loaded NASA or military vehicle stages or tanks, and for future NASA Crew Exploration Vehicle (CEV) systems being designed with SOFI for cryogenic tank insulation planned for launch as early as 2014

E. Appendices

Appendix 1. Principles

Referring to Figure 1-1, as light is incident on a thin dielectric (e.g. ice), a fraction of the light is reflected at the air/dielectric interface, and the rest of the light is transmitted through the dielectric. The transmitted fraction propagates through the dielectric until it reflects off the substrate. The light reflected off the substrate returns through the dielectric until it reaches the dielectric/air interface, where it is again partially reflected into the dielectric and the air. Some absorption of the light occurs as it travels through the dielectric. The internal reflection continues until all the light is absorbed completely by the dielectric.[4,5]

In operation the ice camera measures the spectral contrast between sub-bands in the near IR and compares the measured contrast to a given threshold to determine the presence of ice. Because spectral contrast and ice thickness are related, the relationship between the two may be estimated from an empirical fit of measured spectral contrast and measured ice thickness. The accuracy of the ice thickness relation is dependent on a number of factors, notably the viewing angle to the ice and ice density. As the viewing angle moves perpendicularly away from the ice surface, the spectral contrast decreases for a constant thickness of ice. This effect becomes more significant as the angle becomes greater than 55 degrees from a perpendicular to the ice surface (or a 35 degrees viewing angle from the plane of the ice).

To a first approximation, the MDA ice camera works via specular reflection of the incident energy back to the camera sensor. Since the surface is not perfectly smooth, there is some energy reflected at all angles, though, at less intensity. This is what is known as a Bidirectional Reflectance Distribution Function (BRDF),[10] and Dr. Meitzler suggested this is why the system works even at shallow viewing angles (e.g., 20 degrees).

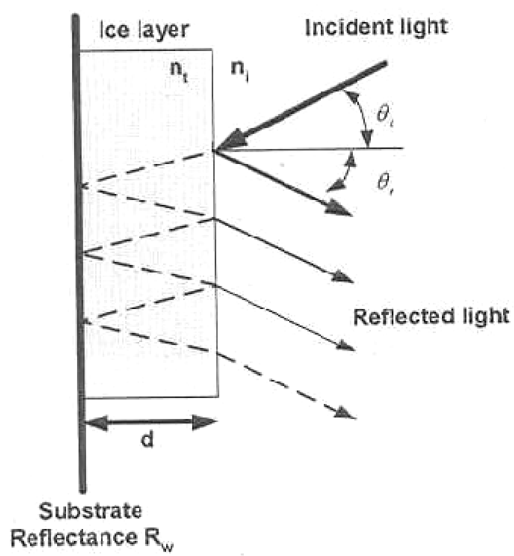


Figure 1-1. Reflection of light from a thin ice layer

For a dielectric of thickness *d*, the effective reflectance $R_e(\lambda, \theta_i)$, of the dielectric layer is given by Equation 1 below:

$$R_e(\lambda,\theta_i) = R(\lambda,\theta_i) + \left[\frac{R_w(\lambda)\left(1-R(\lambda,\theta_i)\right)^2 e^{-2a(\lambda)d}}{1-\left(R_w(\lambda)R(\lambda,\theta_i)\right)^2 e^{-2a(\lambda)d}}\right] \quad (1)$$

Where,

$R_e(\lambda,\theta_i)$ is the effective reflectance

$R(\lambda,\theta)$ is the dielectric spectral reflectance

$a(\lambda)$ is the spectral absorptivity

$R_w(\lambda)$ is the substrate spectral reflectance.

Using specific sub-bands within the near IR region of 1.1-1.4 microns, the spectral contrast is defined by:

$$C = \left[\frac{R_l - R_u}{R_l + R_u}\right] \quad (2)$$

where *l*, and *u* are the lower and upper bands, respectively in Equation 2. Measurement of the reflected energy and the computation of the spectral contrast allows for the detection of ice on a surface and the estimation of the thickness *d,* of the ice on that surface. Below in Figure Y (chart from U.S. Patent #5,500,530[5]), the reflectance is plotted versus wavelength for 0.5 mm ice and water layers with incident light normal to the surface. It is clear from Figure 3 that the IR reflectance of water and ice is very different and linear over a fairly long range.

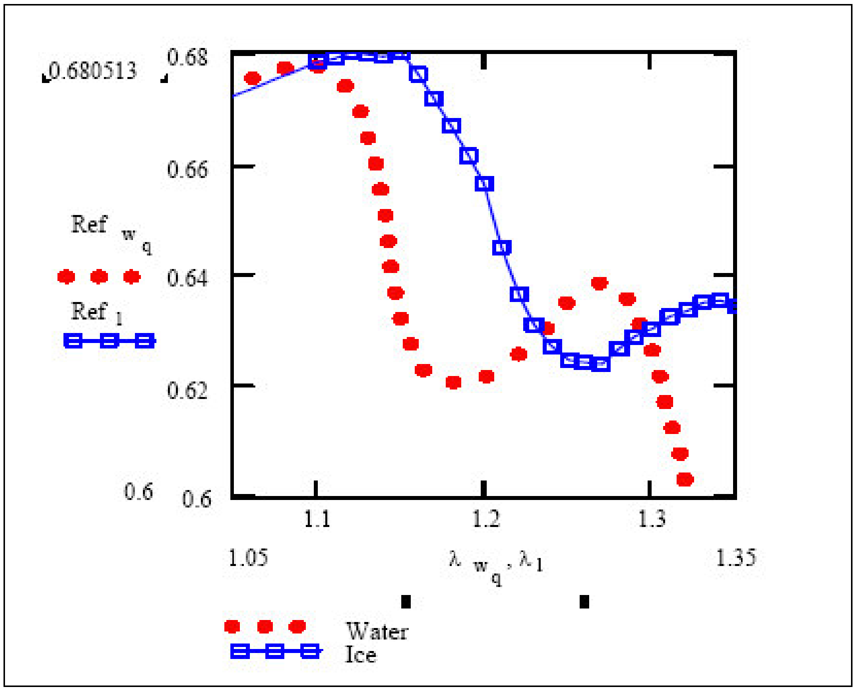


Figure 1-2. Computed spectral reflectance of ice and water versus wavelengthREF[3]

The ice camera utilizes the following generic function for estimating ice thickness (d):

$$\text{Thickness (d)} = K_1 * f(C, K_2)^4, \qquad (3)$$

where, K_1 and K_2 are experimentally determined curve fit parameters, and C is the spectral contrast from Equation 2. For calculations showing the optical resolution and number of pixels as a function of distance for the ice camera, see Appendix 2, Table 2-1 and Figure 2-2.

Appendix 2. Number of Pixels on Target by the Ice Camera

Dr. Meitzler and Mrs. EJ Sohn encoded the following equations to determine the number of pixels on an ice camera target.

$$\mathrm{HFOV} = 2\tan^{-1}\left[\frac{(N_H - 1)d_{CCH} + d_H}{2f}\right] \tag{1}$$

$$\mathrm{VFOV} = 2\tan^{-1}\left[\frac{(N_V - 1)d_{CCV} + d_V}{2f}\right] \tag{2}$$

where:

HFOV, VFOV = Horizontal and Vertical Field of View respectively,

N_H, N_V = No. of horizontal and vertical detectors respectively,

d_{CCH}, d_{CCV} = detector pitch (center to center spacing),

f = focal length.

$$\mathrm{IFOV} = \mathrm{HFOV}/128 = \mathrm{VFOV}/128 \tag{3}$$

IFOV = Instantaneous Field of View

$$\text{Height (one pixel at range R)}: \Delta h = R * \mathrm{IFOV} \tag{4}$$

$$\text{Width (one pixel at range R)}: \Delta w = R * \mathrm{IFOV} \tag{5}$$

The ice camera specifications include: a 128 x 128 focal plane array, each pixel is size 50 microns square, with a 60 micron pitch (pixel center to center), and a 38 mm focal length lens. Table 2-1 shows pixel resolution for a one-in. target at various distances for the ice camera.

Distance (ft.)	Object size (in)	# pixels on object
25	1	2.1
30	1	1.8
50	1	1.1
60	1	0.9
75	1	0.7
100	1	0.5

Table 2-1. Number of pixels on a one in. target

Note: Important for 2007 Selfridge acreage ice and ice ball detection testing and system use, is the number of pixels for a one in. object at a distance of 50 ft. It is obvious why small objects are hard for the system to detect at longer distances.

Figure 2-2 that follows shows the same table values and pixel resolution for a one inch target at various distances for the ice camera. This is based on an 8 x 8 pixel bulls-eye size with the CCD being 128 x 128 in size.

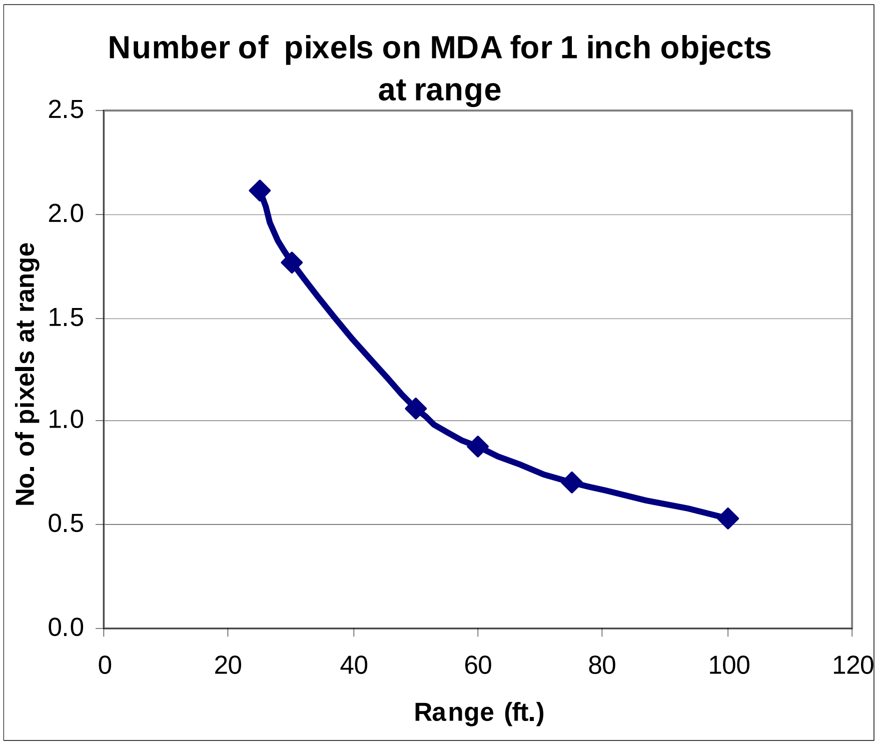


Figure 2-2. Pixels vs. distance for a one inch target

Figure 2-3 below shows the MDA bulls-eye size in inches on the SOFI panel for various ranges for the systems 8 x 8 pixel bulls-eye.

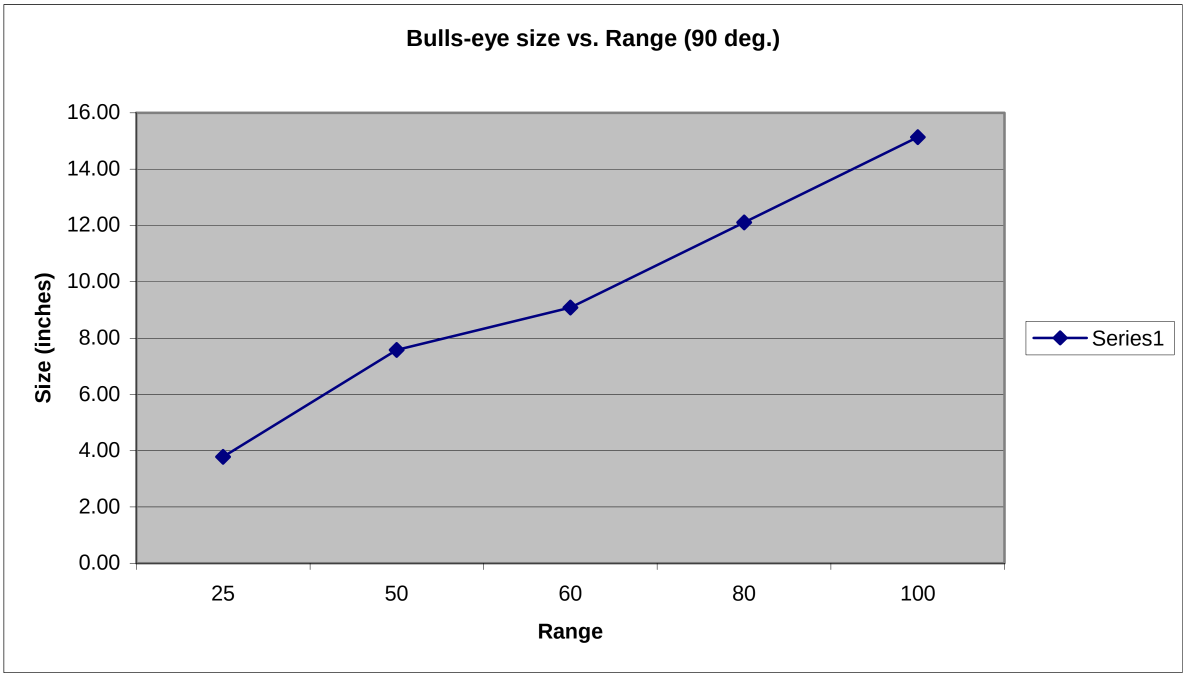


Figure 2-3. Bulls-eye vs. range (90 degrees)

Figure 2-4 below indicates the number of pixels on the ice camera display as a function of viewing angle relative to the surface of a 2 ft. x 2 ft. SOFI test panel for viewing distances of 50, 80, and 100 ft. For example, at 80 degrees and 50 ft. (the blue line), the SOFI is displayed on the MDA ice camera screen about 25 pixels wide (horizontally). At 50 ft. and 45 degrees this diminishes to about 18 pixels since the surface of the SOFI is turned away.

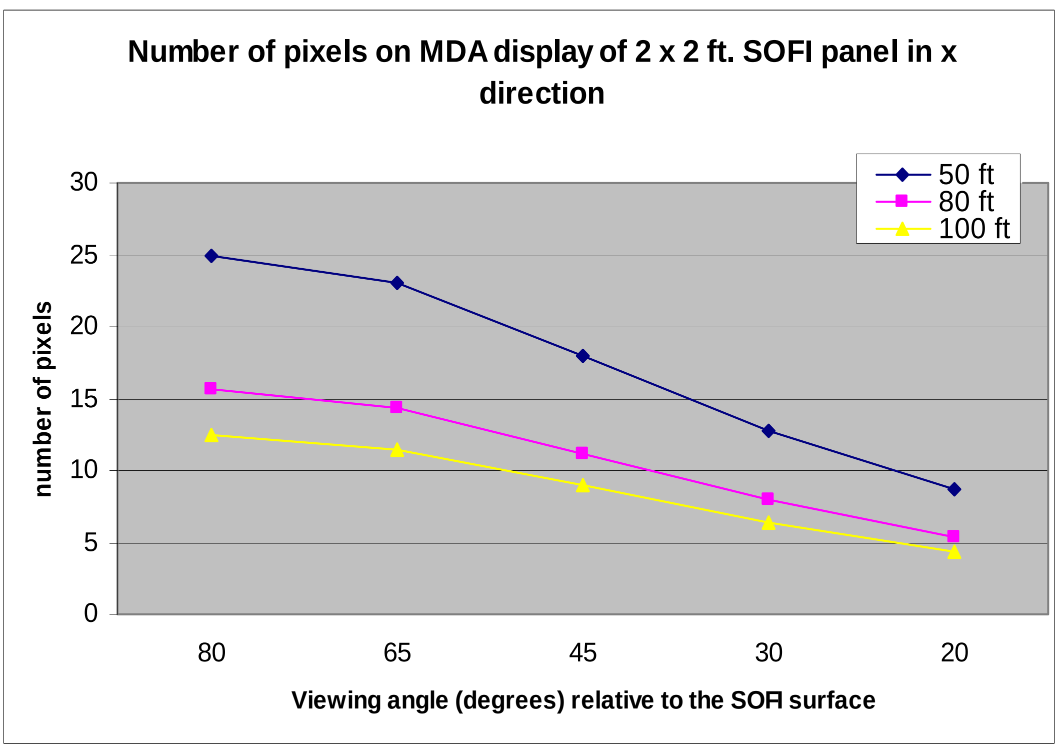


Figure 2-4. Number of pixels on a SOFI test panel by viewing angle

Appendix 3: MDA Maintenance Record

The following is a list of replacement and repairs of ice camera components. In addition, recalibration of the system was accomplished through the updating of ice camera internal system software. It should be noted that this MDA ice detection and measurement system started out as a one-of-a-kind, proof-of-concept system and later evolved as a modified prototype. Components (electrical and mechanical) used to construct the system were off-the-shelf and were *not* designed for extreme heavy testing and long duration operational use.

Date	MDA Maintenance Record Event
	2006
4/06	System recalibrated using March-April 2006 test data.
5/30/06	The connector for the positive flash lamp (strobe) wire and the transformer junction were replaced. Arcing stopped but lamp would not fire reliably. The flash lamp (strobe) and transformer were replaced with new parts, and the system worked reliably. New thickness function algorithm software uploaded into system.
6/5/06	Bias lights replaced. System is working and verified with clean SOFI.
6/9/06	Connector at positive flash lamp (strobe) wire and transformer junction were replaced. Connector arced through to its case. Extra Kapton insulation was added above the connector junction, positive flash lamp wire, and case wall. The System worked, however, there were occasional flash lamp misses. Calibration was verified at MDA with bare SOFI.
7/06	System recalibrated using March, May, and June 2006 test data.
8/15/06	MDA support service recalibration was performed and bias bulbs were replaced.
8/25/06	Two bias bulbs were replaced at NASA-KSC by MDA.
	2007
3/27-4/25/07	System sent to MDA-Canada for repairs because the LCD panel was acting up, and the display screen was not showing consistent ice thickness values. The flash lamp (strobe) was replaced, connectors repaired, the interlock switch box was replaced as were two bias lights. Also the camera swivel mount was replace with an upward viewing changed from 45 to 55-60 degrees to satisfy a NASA request.
5/11-17/07	Bad and scorched connector and some wiring caused strobe not to work and were repaired at MDA-Canada.
5/21/07	VGA to NTSC video converter board replaced at Selfridge.
6/29/07	MDA unit was shipped to MDA-Canada from KSC via TARDEC for inspection, repair, and testing and planned eventual return to KSC for use in support of the STS-118 launch. During inspections a burned connector and wiring were found and replaced as was an interlock switch. The LCD was replaced with a newer unit, and a software change was made for data recording.

Appendix 4: General Testing Procedure

Start-Up Procedure

1. Attach LN2 tank to the SOFI Dewar
2. Weigh the initial weight of the bare/dry SOFI panel that will be tested. Record (in Kaman Excel sheet)
3. Using C-clamps mount desired SOFI test panel to the bare metal part of the Dewar making sure it holds tightly against the surface.
4. Once SOFI is secured open the LN2 valve and start the cool down process.
5. Using the IR camera monitor the fullness of the Dewar. Also check and clear bobber periodically on the Dewar. Brush SOFI panel periodically to ensure clear of frost.
6. Once panel is full, brush frost off panel surface to ensure surface is clean
   a. If there is ice build up on the SOFI surface use heat gun (setting 8) and napkin to dry panel
7. Measure and Record (in Kaman excel spreadsheet) baseline Kaman measurements of SOFI panel <u>before the spraying process.</u>
8. Record initial ambient temperature and relative humidity (RH) into Kaman spreadsheet
9. Spraying Process:
   a. Record start time and end time of each spray
   b. Record the IR surface temperature before and after each spray interval. You probably want to have three people available for the spraying process (person #1- sprayer, person #2-recorder, and person #3-reads off IR temp.)
   c. Between the spray intervals the ice thickness will be recorded with the Kaman until the desired thickness is met. Insert Kaman measurements in column listed in the Kaman Excel spreadsheet.
   d. Once desired thickness is obtained check grid locations: (2,2), (2,3), (2,4), (3,2), (3,3), (3,4), (4,2), (4,3),and (4,4). See Appendix 5 for test panel coordinate reference.
10. Now start MDA and warm-up the strobe for approximately 5-10min. Turn toggle switch on control panel to Ice.
11. Once strobe is steady start the testing process for given distance and angle
    a. Turn on VCR and set to RECORD testing process
    b. Before recording the MDA measurements make sure to speak in to the microphone and state the following:
       - Date (1st time only), time, distance (ft.), panel angle, light on and angle of light (normal/tangential, only when using the solar simulated light source)
    c. Record the Actual test time and MDA system time at the start and finish of each measurement (for distance and angle) See spreadsheets for further details of what needs to recorded. Repeat this step until all angles are done for that one distance.
12. Turn MDA toggle switch from Ice to Visible to turn strobe off.
13. At the end of the session connect laptop to Ethernet port. Login to De-ice camera program and download data log file (make sure to rename file w/ the data, i.e. phase3_5-27-2007.txt).
14. After MDA is done then make the final Kaman measurements of all the grid coordinates and Record into the Kaman excel spreadsheet.
15. Weigh final panel weight on the scale and record into the Kaman spreadsheet. This will then tell us the density of the ice at the particular thickness.
16. Repeat steps 8-15 for all thicknesses, distances, and angles.
17. Upon completion of testing do a complete Kaman measurement of every grid location and weigh panel for final density calculation. See spreadsheet directions for calculating density.

Note for information: Milled–panels #1 and #2, as-sprayed–panels #3 and #4.

Appendix 5: Test Panel Coordinate Reference

This table indicated test cell locations for test panel ice. Example of representative cells used for ice thickness measurement include (2,3) and (4,3).

(Row, Column)				
(1,1)	(1,2)	(1,3)	(1,4)	(1,5)
(2,1)	(2,2)	(2,3)	(2,4)	(2,5)
(3,1)	(3,2)	(3,3)	(3,4)	(3,5)
(4,1)	(4,2)	(4,3)	(4,4)	(4,5)
(5,1)	(5,2)	(5,3)	(5,4)	(5,5)

Appendix 6: Major Equipment Description

The following is a description and listing of major test equipment used for Selfridge ice camera testing.

Kaman sensor: this eddy-current type sensor device, which measures the relative displacement from the sensor head to the underlying metal, in thousandths of an inch, provides an accurate method to measure the ice thickness on the test panel. The model #12CU three-inch sensor head was used for this test.

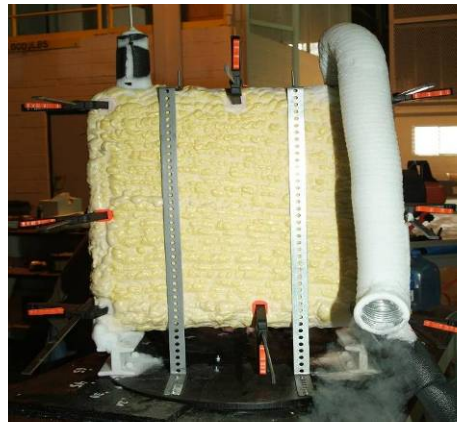
SOFI test panel: 24 in. x 24 in. test panel, representative of ET SOFI (smooth surface and/or as-sprayed), prepared on an aluminium backing plate. Foam thickness should be approximately 1/4-3/8 in. thick, and kept to as consistent a thickness as possible over the entire surface of the sample, in order to maintain a constant temperature for consistent ice formation on the surface. Due to the great thermal insulation this foam provides, very small differences in foam thickness can make a large difference in surface temperature, and so also in ice formation. Machined smooth samples were used primarily for this testing in order to use the Kaman sensor on a flat surface to accurately measure the ice thickness. Smooth samples may be prepared by milling or sanding down as-sprayed samples until the desired thickness is achieved. KSC prepared the samples used for this testing by sanding with a fixed sanding rig custom made for this purpose.

Metal test panel: to simulate non-insulated metal surfaces such as are found on Shuttle umbilicals, brackets, and engine components a 24 in. x 24 in. aluminium plate was painted with the two part epoxy green Koropon paint supplied by NASA-KSC. (See Note [1].) It was found that ice would not stick or form well to the bare test Dewar surface, since it was too cold. For these tests a 24 in. x 24 in. section of 1/4 in. thick sheet insulation (e.g. “BX-250” which can be purchased at most hardware suppliers and is chemically similar to SOFI) was glued to the backside of the painted sample. When clamped to the test Dewar with the foam insulation side facing the cold Dewar face, the painted side was found to be at adequate temperatures for ice growth.

Cryogen: liquid nitrogen (LN2) was used as the cryogen for the Selfridge tests and liquid air was used during earlier KSC testing. Either is adequate for this test. LN2 has a boiling point of minus 321°F, and liquid air of minus 318°F (close to LO2’s minus 297°F, but not as cold as LH2’s minus 423°F–these two cryogens being the oxidizer and fuel stored in the Shuttle’s ET, respectively). A 160-liter Dewar should supply the 24-in. test container for approximately 5-9 hours (depending on ambient temperature).

Cryogen test container (CTC): a 24 in. x 24 in. x 2 in. container fabricated by NASA-KSC of welded aluminium on which to mount the SOFI test panels (see drawing in Appendix 8). The CTC is filled with the cryogen (LN2 or liquid air) so construction and welds must be able to withstand these temperatures, and an adequate exhaust opening must be made to relieve cryogen pressures. The figure below shows the CTC’s bare metal cold plate front surface (Figure 6-1) for mounting the test panels, and the sides and back surfaces (Figure 6-2) insulated with consumer-quality spray-on foam. An open exhaust port for venting can be seen at top left, and the cryogen intake line is attached at the rear left-bottom. The exhaust vent tube was insulated with foam pipe insulation and then expandable uninsulated dryer hose was fitted over the pipe insulation to redirect the cryogen vapors away from the test surface as seen in the figure below.

1 The bare metal sample was painted for these tests to simulate actual NASA metal flight hardware.



Figures 6-1 and 6-2. 24 in. CTC front face w/o SOFI panel and CTC back face with vent and grid straps

CTC cryogen float: constructed of cylindrical cut foam attached to a 36 in. wooden dowel, can be seen at top right of the figure below, which gives a visible indicator of the cryogen level inside. The CTC float port had a cap with a reducer to restrain the dowel rod in a vertical orientation.

Bar Clamps: were used to hold the test panels to the CTC. For the 24-in. test panels, eight standard 18-24 in. bar clamps were sufficient to minimize gaps between the test panel substrate and the cold plate surface of the CTC. The plastic end caps did minimal damage to the test panel SOFI.

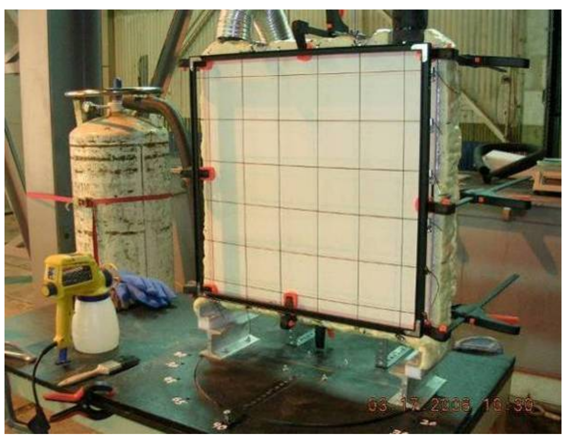


Figure 6-3. Grid and SOFI panel on the CTC

Positioning grid: constructed of a 24 in. x 24 in. metal picture frame and hi-test fishing line spaced at 4 in. intervals, the grid is designed as an aid in positioning the Kaman sensor for repeatable measurements of designated areas on the test panel. The figure above shows a SOFI test panel clamped to the CTC with the grid hanging in position. The extra fishing line border lining the inside edge of the frame is to prevent the Kaman from getting too close to the metallic frame and panel edge. (See Note [2].) As seen in the figures above, galvanized steel straps were used to make brackets to hold two hooks that were aligned with two holes in the top of the grid frame for repeatable positioning of the grid onto the CTC. The grid can be removed easily for water spraying. In 2007

[2] For more information see the Kaman manual section: "Conductive Materials in the Measuring Area".

new welded aluminium tangs were added on the top of the CTC for hanging the grid and these straps.

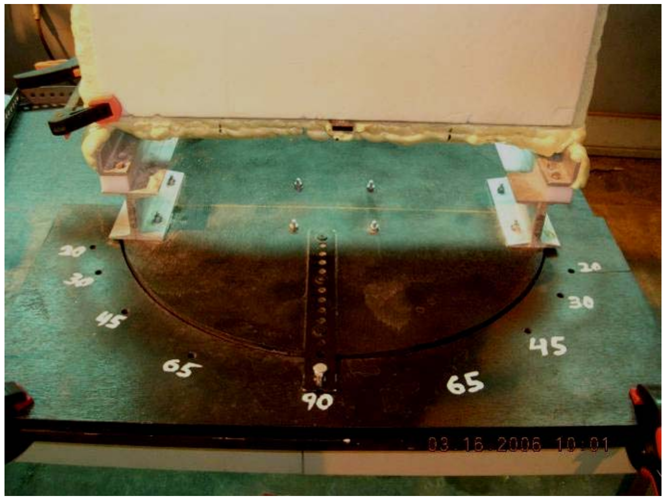


Figure 6-4. Turntable with CTC mounted on top in 90-degree position

Turntable: a custom made rotating platform with angles marked at required positions for rotating the CTC for angular MDA measurements. The table was lockable in each angular position and the CTC should be properly bolted to the turntable for safety. The turntable used in this testing was constructed of 3/4-in. plywood and a 12 in. ball-bearing race. The bottom of the race was mounted to the plywood base, which was clamped to the tabletop with large C-clamps. The rotating turntable section was bolted to the top of the race and the CTC was bolted to the turntable top. Angles were locked into position by inserting a metal bolt through a hole in a metal extension bracket mounted on the turntable into holes that aligned in the plywood base section. For 2007, testing of a similar but simpler design was developed and was constructed of aluminium for durability. The 80 degree marking was added at that time.

Airless paint sprayer: a Wagner 7.2 gallons per hour airless paint sprayer with laser distance guide was used for spraying water for these tests (can be seen in lower left Figure 6-3 above). This type of sprayer appeared to be better suited for this work than the pneumatic type. Since it did not use air to entrain the water, it could be used at a closer distance and deposited the water more efficiently. The spray head (for stain) that came with the sprayer was primarily used.

Infrared (IR) camera: capable of displaying the average temperature of a point or area to monitor the ice/SOFI surface temperature during water spraying for controlling the ice density.

Ice surface tools: a 2 in. high-quality paint brush for brushing frost off of the test surface, a 3 in. x 5 in. fine grade foam sanding block for reducing the ice thickness and removing ice bumps, and a heat gun for warming the ice to increase ice density and for removing ice bumps.

Air convention fan: designed to counteract thermal convection currents on the front of the sample panel to minimize density variations in the ice from top to bottom across the panel surface.

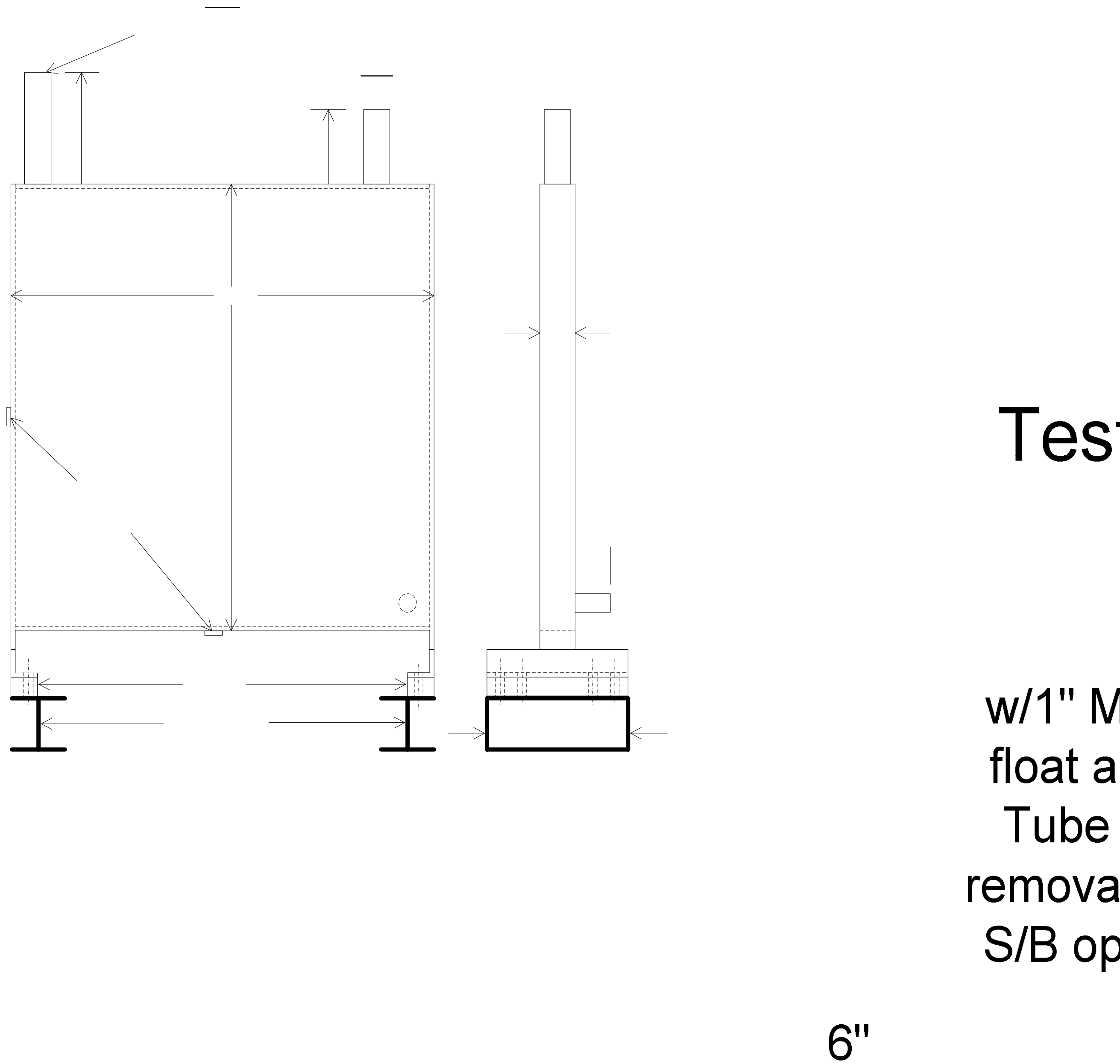
Figure 6-5. Front view of fan assembly

Figure 6-6. Rear view of fan assembly

Appendix 7: List of Required Test Equipment

Item	Comments
24” x 24” test panel(s)	Custom foam panels: may be a single pass SOFI rind, machined SOFI, or BX-250 backed painted metal sample. SOFI thickness should be 1/4-3/8 in. thick.
Air convention fan	To counteract thermal sir convention currents.
Bar clamps (8 each)	18-24 in. size with pistol grip & padded jaws with quick release.
Camera(s), camcorder	For test recording.
Clock/watch	To monitor water spray duration.
Cryogen Dewar	Medium pressure (75 psi) cylinder containing LN2 or liquid air (in enclosed spaces), usable liquid capacity 160 liters.
Cryogen float	Custom built for CTC to monitor LN2 level.
Cryogen line	½ in. line (insulated preferred) with “KC” fittings as long as necessary to connect cryogen supply Dewar and CTC and required wrenches.
Cryogen test container	(CTC) for mounting the test panels - custom built of welded aluminum with open vent and custom float.
Drain tub or area	Sufficiently sized and cryogen safe to allow test panels to melt and drain at conclusion of test.
Flexible ducting	To vent cryogen away from test panel.
Heat gun	For adjusting ice density and removing protrusions (variable temperature preferred).
IR camera	To verify test panel ice temperature.
Kaman sensor	High precision position sensor (eddy current) to measure relative ice thickness.
MDA camera	Custom IR system built by MDA to detect the presence of ice and measure ice thickness for NASA ET and vehicle ice buildup areas.
Monitor(s)	Additional displays to view IR camera, etc.
Paintbrush	2½-in. high quality, for brushing frost off of the test surface.
Personal Protective Equipment (PPE)	Cryogen rated face shield(s), apron, and gloves
Positioning grid	To establish repeatable Kaman measurements–custom made with hooks and straps to hang onto CTC.
Radiometer	To measure luminosity for illumination tests.
Sanding block	For sanding ice (3M brand foam sanding block suggested).
Scale	To weigh the test panels for the density calculation, 14 kg capacity minimum (24 in. SOFI test panels with metal backing weigh about 15 lbs).
Solar lamp	Custom made 2 kW tungsten-halogen lamp bulb housed in a cylindrical deflector.
Spray gun	Wagner 7.2 gallons per hour airless paint sprayer with laser distance guide or equivalent.
Temperature/RH sensor	For recording environmental conditions.
Turntable	Custom made rotating platform to provide angular rotation of CTC with respect to MDA. Line of sight should be properly aligned to MDA, required angles marked, and positions lockable.
Water storage container(s)	For refilling sprayer as needed (1 gal. jug).

Appendix 8: Drawing of Cryogen Test Container (CTC)



Appendix 9: Experimental Techniques

It should be noted that the development of test procedures and processes identified in this Appendix are a contribution to ice system testing. Anyone interested in ice development and testing should be interested in the use of this methodology. Addressed in the appendix are: a) Kaman ice measurement, b) ice formation, c) ice adjustments, d) ice density, e) water type, and f) a step-by-step procedure. Since procedures for this type of experimental testing are unique and innovative, their development and use are very important to future ice system testing by TARDEC/NASA and others.

Kaman Measurements

The Kaman sensor should be allowed an adequate warm up time (15 minutes) and should be re-calibrated daily (see calibration procedure that accompanies the Kaman unit). With the test panel mounted to the CTC, twenty-five baseline measurements are taken across the foam surface of the bare test panel (clear of ice or frost), in locations indicated by the positioning grid. The measurements should be taken shortly after liquid cryogen is present in the CTC (as indicated by the float bobbing) so that there aren't any thermal effects on the measurements. If frost bumps have formed on the SOFI prior to Kaman baseline measurements, they can be removed by using the heat gun (being cautious to keep from burning the SOFI) and blotting the melted drops with a paper towel. The positioning grid is used to provide a repeatable positioning of the Kaman sensor head for subsequent measurements. After ice has formed the baseline measurements can be subtracted (e.g. using spreadsheet software) to calculate the ice thickness. Kaman measurements should be done regularly during the ice formation stage to check ice thickness, and during testing to maintain thickness.

Ice Formation

For these tests an airless paint sprayer was used to form ice on the test panels. A degree of expertise and consistency in water application is required to obtain the desired ice thicknesses and densities. With some practice in spraying and sanding techniques, ice thicknesses within a few thousandths of an in. of the targeted thickness can be formed and held constant for hours. The ice formation depends on the test panel surface thermal "inertia," ambient temperature, ambient humidity, and water spray techniques.

a. **Test panel surface thermal "inertia"**, as used here, refers to the thermal conduction properties of the surface (SOFI, metal, or ice) and the heat capacity of the sample panel as well as any ice previously formed. The energy of the liquid water sprayed onto the surface must be absorbed and conducted in order to freeze the newly sprayed water. The minimal heat capacity of the SOFI as well as its low thermal conductivity, lead to very low initial ice formation rates on the bare SOFI surface. Once ice has formed, the heat capacity increases and ice formation rates increase. The first several (5) applications of water spray on the bare SOFI should be of short duration (about 5 seconds), and/or from a further spray distance (about 18-24 in.). If too much water spray is applied, the water may tend to drip and then freeze forming an uneven ice surface. The surface temperature can be monitored with an IR camera that shows average temperature in a target region (if available, the IR camera output can be input to a larger monitor for easier observation by the person doing the spraying). Once a thin layer of ice is achieved (0.005-0.010 in.) spray duration may be increased (10 seconds or longer).
b. **Ambient temperature** plays a role in ice formation, even though it's mostly overshadowed by the extremely cold cryogen. It is important to consider ambient temperature, however, in maintaining the cryogen level in the CTC, since higher ambient temperatures will cause a

greater rate of cryogen venting. To form consistent ice it's important to keep a sufficient cryogen level at all times during the course of the test. Ambient temperature and humidity also play a role in dew point which effects frost growth on the test surface. Spraying on top of the frost, which grew since the last spray will cause the ice to have a lower density, so for higher target densities the frost should be brushed off.

c. **Ambient humidity** also plays a role in frost formation on the test surface, and this can affect the ice density, as mentioned above.

d. **Water spray** technique, timing, and duration are important considerations for the consistency in ice thickness and density requirements. The airless sprayer used for these tests has four settings, but the "house" setting, which gave the highest spray rate, was primarily used (each setting adjusted the frequency of the spray). The "general use" paint head was used for its even distribution and consistency in spray pattern. The test surface temperature just before, and immediately after spraying, should be monitored to maintain ice density characteristics. The dominant factor in the density of the ice formed is the surface temperature reached at the end of the spray. Since frozen water drips are difficult to remove, it is important to develop a feel for how much spray the ice will allow before too much melting or dripping occurs.

At least the first five sprays on bare SOFI or metal should be of short duration (about five seconds) and from further away (about 18-24 in.) to prevent dripping. It is important to note that this initial thin ice, if used for testing, has a high density, since the SOFI surface thermal conductivity is so low and the initial sprayed water will not freeze as quickly. Once a thin layer of ice has been established (0.005–0.010 in.) the test surface should be able to handle (thermally) spraying from 18 in. with 10-second durations for the next series of sprays. Once significant ice has formed (0.050 in. minimum), the duration can be increased to 15 seconds. In general, more attention should be given to the spray technique and pattern, rather than trying to fit in the exact time duration. However, monitoring the clock is important, not only for individual spray durations, but also for cumulative spray time as well. Given that good consistent spray technique has been established and the environment remains constant the ice thickness may be estimated using the cumulative spray times. After the initial ice base is formed (0.020 in.), a good assumption is that approximately 0.0005 in. to 0.001 in. of ice is added per second of spraying. In order to establish a consistent ice thickness, water spray should be evenly distributed. Good technique is to maintain a constant distance to the surface, moving the sprayer parallel to the plane of the surface, as is recommended in good painting technique. Always start the sprayer pointed slightly away to one side of the test surface to avoid any inconsistent startup spray (especially after refilling the sprayer). For good ice thickness consistency, alternate from horizontal to vertical spray patterns, alternate directions (left to right, right to left, etc.), and vary the starting points (e.g. if started at top left, then start at top right next time, etc.).

Ice Adjustments

During the course of an experiment, frost and/or ice crystals may grow on the ice thereby increasing the ice thickness and reducing the ice density. There are several techniques to adjust ice thickness and density to maintain a more constant ice state.

a. **Paintbrush:** light frost can be blown off with compressed air, but it's more effective to brush off (with a good quality paintbrush). If lower density ice is required, simply let some of the frost grow. It is important to keep the brush dry so that it does not apply water to the ice surface creating ice bumps.

b. **Sanding block:** surface irregularities and higher density frost may need to be sanded off (with a foam sanding block). A light-touch circular sanding with the foam sanding block will take off a

few thousandths of an in. or more for locally adjusting ice thicknesses. Often at the lower third of the test panel where air convection reduces the ice surface temperature, low density ice protrusions will form, thereby reducing the ice density at the lower part of the panel. The sanding block is effective at removing the protrusions.

c. **Heat gun:** is needed for removing the ice bumps that form on bare SOFI before spraying starts. Use an absorbent paper towel to blot the drops after they've melted with the heat gun. The heat gun may also be used for melting the ice to increase the density or reduce thickness, however, use it cautiously, since it can quickly "crater" or make the ice uneven. Remember you must overcome the latent heat of the ice before it changes phase, and so it may appear not to be melting and then melting appears suddenly, possibly with drastic results. A heat gun with an adjustable temperature can help.

Ice Density

Density or mass/volume is calculated as the weight of ice (SOFI test panel with ice minus SOFI test panel without ice) divided by the volume of ice (thickness x area). Ice thickness can be determined by averaging the measurements over the entire test panel (one from every grid cell, 25 total, as measured by the Kaman). The surface area where ice did not form, such as under the clamp pads, may be considered compensated for by the extra ice that can form on the edge of the test panel. In such a case where there is no ice extending past the edges of the panel, the area of the clamps can be subtracted from the calculation (e.g., 8 clamps, at approximately 1 inches square = 8 square inches).

For ET simulation, ice density is considered to be in the range 30-40 lbs/ft^3; however, other densities for this testing were also investigated. Target density can be achieved by the careful application of water spray by monitoring the spray duration time, the surface temperature (as determined by the IR camera), and by sanding and/or warming the ice (e.g. with the heat gun).

a. **30-40 lb/ft^3 density ice:** the spray can be initiated once the surface temperature is below 10°F but before it reaches minus 10°F. The more important parameter is the surface temperature at the end of the spray session. For the upper part of this density range, the end temperature should just reach the freezing point of 32°F for most of the sprays. For the lower part of this density range fewer of the sprays may end at 32°F. Frost must be brushed off of the surface before each spray.

b. **20-30 lb/ft^3 density ice**: the spray sessions will be similar to the 30-40 lbs/ft^3 density ice except that the spray should start when the surface temperature of the ice is between 0°F and minus 15°F. The spray sessions should last until the ice surface temperature is between 23°F and 28°F. Excessive frost should be brushed off and protrusions should be sanded just enough so that they are structurally firm enough to support the Kaman sensor head without crushing. Some protrusion growth throughout this process is desired to create this low density ice. The protrusions should not be significantly melted away during the spray sessions.

c. **40-50 lb/ft^3 density ice:** the spray sessions will be similar to the 30-40 lbs/ft^3 density ice except that the spray should start when the surface temperature of the ice is between 15°F and 0°F. All of the spray sessions should last until the ice surface temperature is at the freezing point of 32°F. The spray should last long enough that the indicated temperature remains at the freezing point for some time but care must be taken so that the spray ends before dripping on the ice surface occurs. Frost should be brushed and protrusions sanded as before but due to the higher surface temperatures for this density, there should not be much frost growth and very few, if any, protrusions.

d. Very low density (< 20 lb/ft^3): can be achieved by permitting frost to grow, spraying over the top of frost, and spraying at colder temperatures (e.g. minus 20 to minus 10°F), and/or with shorter durations (e.g. 5 seconds at a time). The idea is not to let the ice get too wet, since melting will remove the air and raise the density. Ice of this type will look more white or frosty, and be more opaque, and may appear "crunchy" to the touch.

e. Very High density (> 50 lb/ft^3): might be achieved by spraying at higher temperatures (e.g. +10 to +20 ° F), and for longer durations (e.g. 15 seconds), until just before drips begin to appear. Also, keep the surface completely clear of frost. If frost develops, it can be brushed off with a paint brush, if it's of a very light density, or if it is more of a "crunchy" type, can be sanded lightly with a foam sanding block. Additionally, the ice can be warmed to the melting point by using the heat gun, which will reduce the amount of air in the ice (being careful, so as not to warp or "crater" the surface). Ice of this type is quite transparent and hard, and cracks develop as it freezes. Note, that for comparison, ice cubes as formed in a freezer have a density of about 57 lb/ft^3. Achieving these higher densities by spraying water has proven to be difficult, for the ice has to be nearly air free. Therefore, the water spray needs to be frequent to prevent any frost growth and always on the verge of melting the ice.

Water Type

For the majority of this testing, only tap water was used; however, some limited testing was done using saltwater to simulate the higher saline content of humidity at KSC. Although, this was not expected to have much of an effect on the ice, since the salt should be excreted out to the surface during the freezing process. (See Note [3]), it was actually observed to form a lower density ice with fine hair-like structure. This, of course, is contrary to what one would expect, since the salinity lowers the freezing temperature of the water, and therefore a higher density ice would be expected. At the time of this writing, we have no explanation for this phenomenon.

Step by Step Procedure

a. Setup

Note: Any person in the area of any quantity of cryogen should have appropriate training and must be wearing appropriate Personal Protective Equipment (PPE).

1. **Collect** equipment listed.
2. **Configure components** by placing the CTC on a table or other elevated stand and connect its supply port to the liquid cryogen source. Install vent hardware and cryogen float.
3. **Prepare computer** with a spreadsheet for recording data
4. **Weigh test panel** and record for density measurement.
5. **Mount test panel** onto CTC using bar clamps (8).
6. **Record** ambient temperature and RH.
7. **Begin cryogen flow** into CTC (check fittings and lines periodically). The cryogen supply valve should be opened until liquid is present in the CTC at which time the supply valve should be closed until it is just slightly open.
8. **Position clock and IR camera** display so that they are easily visible to sprayer operator. IR camera emissivity should be set to 0.98, which is the value for ice. Set the IR camera to display the average temperature in an, approximately, eight by eight in. square in the

[3] Freezing water has been known to be used for purification of brackish water, since impurities are excreted out.

center of the test panel.

9. **Calibrate Kaman** sensor per placard instructions.
10. **Hang grid** in front of test panel.
11. **Measure baseline** (bare surface – no ice) using the Kaman, take measurements in the center of each of the 25 grid locations and record readings in a spreadsheet or similar datasheet. These measurements should be taken approximately one minute after liquid is present inside of the CTC as indicated by the bobbing float, but before significant frost has formed on the SOFI. If frost has already formed, brush away completely or melt using the heat gun.
12. **Remove grid** in preparation for spraying.
13. **Setup sprayer** (if using Wagner sprayer set to "house" setting), fill with water, and spray (away from test panel) until primed.

b. Spraying

1. **Brush frost** away from the surface as needed before each spray (unless low density ice is desired).
2. **Monitor surface temperature** with the IR camera for desired ice density spray temperature range per **Ice Density** section above. Record start temperature.
3. **Spray** moving perpendicular to the plane of the surface with even strokes at a distance of 18 in. Vary spray pattern to ensure even ice thickness. If dripping occurs, stop the spray and immediately dab the drips with a lint free absorbent cloth or similar. If excessive dripping does occur, the spray duration is too long for the conditions and should be reduced or the panel is too warm. Initial spray durations should be about 5 seconds until several thousandths of an in. of ice is built up (about five 5 second sprays). Once ice is developed spray durations can be increased to 10 seconds until approximately 0.050 in. of ice is present and then 15 seconds durations may be used. Approximately, 0.0005 in. of ice is added for every 1 second of spraying after initial 5-second sprays. After the first five 5 second sprays, the main criteria for the spray duration is based on the temperatures listed in the **Ice Density** section above for the desired density, with the time durations then becoming secondary.
4. **Monitor surface temperature** with the IR camera and record the indicated average temperature after the spray is completed.
5. **Sand** lightly, if needed, to remove unwanted protrusions or excess frost on the ice surface (unless low density ice is desired). The heat gun may also be used but should be considered a last resort since it is much harder to control than the sanding block. The only exception is for ice 0.020 in. or thinner where the risk of damaging the underlying foam would be too great to use the sanding block, and in such case, the heat gun should be used exclusively. If using the heat gun, care must be taken to absorb any drips with a clean cloth or sponge before they refreeze.
6. **Brush frost** away from the surface to avoid affecting the Kaman measurements
7. **Check ice thickness** with the Kaman and grid periodically such as after the first five sprays. After the ice reaches 0.020 in, the ice creation rate does not change dramatically so if the thickness changes 0.0005 in. per second of spray, that rate can be used to estimate how many sprays to make to reach a target ice thickness. Care should be taken not to over shoot the target thickness since it is much easier to add a few thousandths than it is to sand a few thousandths off. Also, undershooting the target value allows for localized spraying if one part of the panel has thinner ice than the rest. Record temperature and RH at time of measurements.
8. **Repeat** steps 1-7 until desired ice thickness is achieved.

9. Depending on the application for which the ice was created, it may be necessary to brush the frost from the ice surface periodically to maintain the desired ice state. Less often, ice protrusions will grow naturally and will need to be sanded if the ice thickness is to be maintained. Repeat step 7 as necessary.

c. Post Test

1. **Remove clamps and weigh** the test panel on a scale and record the final weight. The ice density can now be calculated from the difference in initial and final weights (weight of just the ice), and the calculated average ice thickness.
2. **Close cryogen supply** valve.
3. **Place test panel in a bin** or sink so that the water from the ice melting will not damage anything. Care must be taken in how the test panel is placed so that the SOFI is not damaged.

Appendix 10: Thick Shell Ice Ball Testing Procedures (2007)

General Notes:

- This procedure requires the use of air brushing techniques.
- Frost should be removed through brushing before spraying.
- When spraying a SOFI test panel, the Wagner sprayer should be moved in a plane parallel to the plane of the SOFI at a distance of 16 to 20 in.
- Sanding or ice shaping can be done during the ice build to remove protrusions or drips on the ice surface.
- If using Kaman to measure ice thickness, brush off the frost and then take measurements quickly to prevent ice surface from chilling before spraying is resumed.
- Before first spray or after refilling the sprayer, run sprayer away from panel to prime.
- A very rough estimate is that 0.0005 in. of ice will be added for each 1 second of spraying on the 24 in. x 24 in. panel after the 5 second sprays are completed.

Test setup–base ice on sample panel

- Ensure that the test Dewar is connected to the supply Dewar.
- Mount SOFI test panel onto test Dewar using bar clamps.
- Open supply Dewar valve.
- Monitor float for movement indicating liquid is present then reduce cryogen flow using supply Dewar valve.
- Throughout the rest of the testing, continuously monitor the cryogen float and adjust the supply Dewar valve accordingly.
- Set clock/watch and IR camera display so that they are easily visible to sprayer operator
- Fill sprayer with water.
- If using adjustable Wagner sprayer set to highest frequency spray setting, this is indicated by a house icon.
- Calibrate Kaman sensor per instructions.
- Measure and record baseline SOFI thickness with Kaman.

Test setup–ice balls

Notes:

1. It was found that ice balls do not require an ice base on SOFI, but may be adhered directly to a bare SOFI test panel. The method uses an ice ball mold to melt the flat side then hold it to the surface until it freezes. See the section below titled: **Adhering ice balls to SOFI.**
2. Ice ball creation (may be done in parallel with "Test setup–Base ice preparation on sample panel" above).

- Connect airbrush to compressor.
- Fill 2 oz. airbrush bottle with water and connect to airbrush.
- Lay 12 in. x 12 in. test Dewar on its back and connect to cryogen supply source Dewar.
- Lay SOFI sample panel, partially insulated on exposed face.
- Lay molds on uninsulated portion of sample panel.
- Slightly open supply Dewar valve to chill test Dewar.
- Adjust flow to maintain liquid in test Dewar.

Note: The rest of this section can be used to create three ice balls each of 1, 2, and 3 in. diameters.

- A few minutes after frost begins to form on the molds, spray to fill ice ball mold with airbrush sprayer.
- Do not spray enough to wet the ice surface and don't start a spray until the ice surface is glazed or very slight frost has formed. Suggest spreading the spray among all or at least a few molds to avoid over spraying and creating high density ice.
- If significant frost has formed on the frost surface, remove using air or a brush before spraying.
- Once mold is filled, shape by sanding or other to make ice surface flush with the top of the mold. Using proper Personal Protective Equipment (PPE) gloves, dip mold into warm water to release ice ball.

Weigh ice ball and record weights in table below:

Number	Ice Ball Size	Weight (g)	Density
1	1		
2	1		
3	1		
1	2		
2	2		
3	2		
1	3		
2	3		
3	3		

Note: Density = $[(\text{weight}/453.59)/(2/3*\text{pi}*(r/12)^3]$ lbs/ft^3

If SOFI panel has an ice layer of sufficient thickness, adhere ice balls to the panel per ice ball testing section below. Otherwise put ice ball into a plastic bag inside a freezer.

Base Ice Preparation on Sample Panel
Note: May be done in parallel with ice ball creation.

(Repeat following two steps four times).

- Monitor panel surface temperature.
- If temperature average is between -10 and -5°F, spray panel for 5 seconds.

(Repeat following two steps 5 times)

- Monitor panel surface temperature.
- If temperature average is between -5 and 5°F, spray for 10 seconds.

(Repeat following two steps 5 times).

- Monitor panel surface temperature.
- If the surface temperature does not exceed 28°F following the completion of the spray, subsequent spray times may be extended to 15 seconds. Reduce spray times if ice surface dripping is noted and increase the sprays to 7 repetitions.

- Measure ice thickness by subtracting baseline SOFI thickness from Kaman measurements.
- If average ice thickness is approximately 0.060 in., proceed with ice ball adhering.

Ice Ball Testing

- Turn the test Dewar to 90 degrees (vertical).
- Mount grid to test Dewar.
- Adhere ice balls using a hand water sprayer in the following locations:

Grid Location	Size (in.)
1,1	1
1,3	2
1,5	3
3,1	2
3,3	3
3,5	1
5,1	3
5,3	1
5,5	2

- Remove grid.
- Move the ice detector to 60 ft. distance.
- Turn on ice camera.
- Aim ice camera at the center of the SOFI sample panel.
- Turn on ice camera strobe and VCR.
- Per the tables below move the test Dewar or ice camera to the test configuration indicated.
- Brush frost between every measurement if necessary.

Record in the following table whether the ice camera indicates the presence of the ice ball for XX ft. and YY degrees.

Grid Location	Size (in.)	Visible?	Steady?	Comments
1,1	1			
1,3	2			
1,5	3			
3,1	2			
3,3	3			
3,5	1			
5,1	3			
5,3	1			
5,5	2			

Following the detection part of the test, the video can be analyzed as stills to graphically measure the ice ball diameters at 90 degrees relative to the size of the panel itself or relative to each other.

Adhering ice balls to SOFI

- Ice balls may be adhered directly to the bare SOFI test panel. The back side of one of the ice ball molds (or any similar large base of metal block) can be used as a thermal sink.
- Using thin thermally insulating gloves place the ice ball flat side onto the thermal sink briefly and slide it around softly until wet. This should take no more than 5 seconds.
- Pick up the ice ball and quickly hold against the SOFI until it has time to re-freeze. Depending on the SOFI temperature this may take 10 to 30 seconds.

Note: A technique to remove the ice balls from the SOFI by scraping without damaging the foam has not been proven successful yet, and the investigators have found it better to let them melt naturally, however, inducing melting with a heat gun may also be used.

Appendix 11: Thin Shell Ice Ball Development Procedure (2007)

Notes:
1. The following procedure was developed by Greg Smith of TARDEC and Thomas Moss of NASA-KSC for creating thin shell ice balls from male and female molds fabricated by NASA and provided to TARDEC for testing purposes.
2. Thin shell molds were made in three sizes–one, two, and three inch diameters.
3. The following procedure is applicable to forming ice ball hemispheres regardless of test diameters.

Procedural Steps

1. Pour water into the female mold enough to fill or cause overflow when mated with the male half (about half full). Insert the male half.

2. Set the mold onto the horizontal Dewar for freezing. On a fully chilled Dewar this should take less than fifteen minutes. See Figure 18.

3. Freezing should be finished when water is seen squeezing out the compression slot.

4. Using cryogen safe gloves carry the mold to the sink and with a hose sparingly apply warm water to the sides of the bottom half of the mold, checking often to see if the male half can be turned to loosen it from the mold. Too much water may cause too much melting of the ice shell. Note: the melting point of ice is a few points above the freezing point, so when enough thermal energy is added to overcome the freezing point, melting can occur suddenly. To be safe, check a few times to see if the mold can be loosened.

5. As soon as it can turn slightly remove the male half from the mold. The ice shell will adhere to the male half and it can then be carefully wedged off with a thin plastic putty knife and dropped into a plastic bag and placed in the freezer. Shells should be handled sparingly or not at all since they are quite thin and fragile. Insulated gloves or thin vinyl gloves can offer some help in handling.

6. Once brought back to a frozen state in the freezer, thin ice shells can be packed with frost and weighed for the density calculation. (Frost can usually be gathered from the Dewar vent tubes for this purpose). The bottom half of the ice mold (female) can be used to hold the thin shell while filling with frost.

7. Filled or unfilled thin ice shells can be adhered to the bare SOFI panel the same way as the thick shell ice balls as described in Appendix 10 and shown in Figure 17.

Appendix 12: Error Analysis of Density

Note: The following was developed by Darryl Bryk of TARDEC.

From the density formula: $\rho = \dfrac{m}{V} = \dfrac{m}{At}$ where: m = mass
V = volume
A = surface area
t = thickness

the uncertainties (δ) can be investigated in m, A, and t.

Propagation of uncertainty

The "uncertainties in products and quotients" formula[1 pg. 61] states for a function $q(x, \ldots, w)$:

$$\frac{\delta q}{|q|} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \ldots \left(\frac{\delta w}{w}\right)^2}$$

Uncertainties

Weight (m): when not explicitly known, the uncertainty of a digital display can be taken as ± the last displayed digit.[4 pg. 47] Therefore, the uncertainty for the scale that was used for weighing samples is assumed to be:

$$\delta m = \pm\, 0.01 \text{ lbs.}$$

Surface area (A): for the SOFI panel assume an uncertainty of ± 0.1 inch in each dimension. Therefore, for the 24 x 24 inch panel:

$$\delta A = |24 * 24| \sqrt{\left(\frac{0.1}{24}\right)^2 + \left(\frac{0.1}{24}\right)^2} = \pm\, 3.39 \text{ sq. in.} = 0.024 \text{ sq. ft.}$$

Thickness (t): based on over 400 Kaman measurements of five repeated readings at approximately the same grid location[5] an average standard deviation (n-1 type) for the Kaman was calculated to be:

$$SD_K = 0.00085 \text{ inches}$$

From this an uncertainty δt for ice thickness measurements can be calculated as:

$$\delta t \quad \text{inches}$$

Since m, A, and t, are independently measured quantities, we can calculate the relative uncertainty these will cause in the density calculation $\delta\rho$ from the propagation of uncertainty formula given above as:

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[4] From "An Introduction to Error Analysis", by John R. Taylor, University Science Books, 1997.
[5] Data based on over 400 measurements from 2006 testing at Selfridge (SANGB).

$$\delta\rho = |\rho|\sqrt{\left(\frac{\delta m}{m}\right)^2 + \left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta t}{t}\right)^2}$$

Plugging in the numbers for data taken this year from 2/26 - 3/12/2007 a graph of $\delta\rho$ is plotted (below) for various ice thicknesses. As can be seen in the graph below, the average ranges from 0.86 lbs/ft^3 for 0.04 inch ice to 0.36 lbs/ft^3 for 0.25 inch ice. Since surface area *A* is basically a constant, we see as ice thickness *t* increases and therefore also *m*, $\delta\rho$ decreases.

The chart below shows some sources of the data and averages used in the calculations above.

#Samples	16	32	40	60	60	36	60	60	60	424
Kaman 5's S#1	**6/13/06**	**6/14/06**	**6/15/06**	**4/4/2006_t1**	**4/4/2006_t2**	**7/13/06**	**3/30/2006_t1**	**4/3/2006_t1**	**4/3/2006_t2**	**AVG**
AvgStdDev	8.5E-4	12.7E-4	10.2E-4	7.6E-4	7.4E-4	7.0E-4	7.5E-4	8.4E-4	7.4E-4	8.5E-4
AvgUncertainty (/sqrt(n))	3.8E-4	5.7E-4	4.5E-4	3.4E-4	3.3E-4	3.1E-4	3.3E-4	3.7E-4	3.3E-4	3.8E-4

Appendix 13: Future Operational Ice Camera Requirements

	Requirements	Specifications
A. OPERATIONAL PERFORMANCE/CAPABILITIES		
A-1	Full range of STS inspection targets	• Prime–STS inspection include of SOFI and PDL • Secondary–target material surfaces/areas including: SLA, LO2 feed line brackets/bellows, SSME, dome heat shield area and O2 vents, EB fittings, ET/ORB umbilical areas, and the GH2 vent arm
A-2	Minimum ice detection thickness and display	• 0.4 mm. (0.015 in) or better
A-3	Range of ice thickness measurements	• 0.4 to 13 mm. (0.015 to 0.500 in)
A-4	Minimum/maximum operational distance	• 7.6 m. (25 ft) min. to 24 m. (80 ft) max. • Max. target 38 m. (125 ft)
A-5	Maximum viewing angle range	• 0 (normal) to 70 degrees
A-6	Spatial resolution at maximum distances	• 2.5 cm. (1.0 in) @ 19.8 m. (65 ft) • 7.2 cm. (3.0 in) @ 38 m. (125 ft)
A-7	Minimum measurement update rate	• 1/2 Hz. (1 Hz. target)
A-8	High quality operator display in bright ambient light	• VGA resolution min. • Shield provided for sunlight viewing • A display illumination of at least 800-1000 nits (sunlight readable)
A-9	Ambient lighting conditions	• Night to full sun display viewing • 25 foot candles min.
A-10	High reliability (MTBF)	• 500 hours (with simple component change outs)
A-11	Minimum UV emission	• Device UV must not trigger launch pad fire detectors • No UV emission below 300 nm
A-12	Range of outputs and formats	• Retrievable recording of visual and IR images and uncompressed (raw) data
A-13	Video/data recording	• Digital recoding (e.g., DVD or digital flash drive) of data for post-inspection analysis • Switch position and time stamp recordings for ice density analysis and determination
A-14	Ice density compensation	• High (≥ 35 lb/ft^3), medium (20-35 lb/ft^3), and low (≤ 20 lb/ft^3) ice density operator switching
A-15	Operator manual sensor head pan, tilt, and locking	• Movement of sensor head up and down and side to side with fine adjustment (±10 degrees vertically and horizontally) • Functionality to easily move, lock, and unlock the head
A-16	Built-in-test system readiness capability	• Built in critical function tests with displays to indicate system operational readiness or failures
A-17	Minimum operating time	• Two hours continuous on battery power • Eight hours continuous on ground power
A-18	System ranging for ice	• An eye safe (Class 3A or less) laser ranging system capability

	Requirements	Specifications
	density/mass determination	for determining distance from the sensor to a target with an accuracy of < 1cm. • Target capability to use distance to determine the IR strobe pixel target area, coupled with ice thickness measurements to determined ice volume, and mass-energy • The ranging laser will be on only during ice thickness measurement.
A-19	Target visibility/location	• A matching field of view for IR and color images • In the IR view, functionality is required for the operator to identify the area of a target object
A-20	Movable target circle	• Operator capability to move the target circle in an image to fine tune target location without moving the sensor head
A-21	Run-time timer	• Cumulative IR run-time determination since the last service/calibration via the on-board processor clock
A-22	Target area determination	• Operator in real-time needs the capability to determine and display the area of a target object
A-23	Post-inspection data analysis capability	• Application software for PC-based system data analysis capability
A-24	Adjustable bulls eye	• Variable cursor target adjustment for post-inspection data analysis
A-25	System variability	• Variability should be ±0.008 in.
	B. PHYSICAL	
B-1	Maximum weight	• < 70 kg. (155 lb) • Target ≤ 64 kg. (140 lb)
B-2	Transportability	• Transportable in a full-sized van without disassembly (e.g. Chevrolet or Ford)
B-3	Maintainability	• Simple access to replaceable components on site by NASA or MDA personnel • Access to uncompiled software application and configuration files
B-4	Full ambient operating temperature range	• 0 to 40 °C (32 to 100 °F)
B-5	Storage temperature limits	• -10 to 51 °C (15 to 125 °F)
B-6	Maximum relative humidity operations	• 100% and waterproof for possible transport and use in the rain
B-7	Explosion proof	• Capable of maintaining GN2 inerting pressure for 3 hours min. Ref. KSC STD E002: Hazard Proofing for Electronically Energized Equipment, Standard 4.
B-8	EMI	• FCC Class A
B-9	Shock isolation	• Tip over drop test of 30 cm (~1 ft)
B-10	Design assurance level	• MDA Level C
B-11	Vibration	• Design should include locking connectors when possible • A roll around test will be required
B-12	Acoustic levels	• N/A
	C. USER INTERFACE	

	Requirements	Specifications
C-1	Display characteristics (e.g., color scheme, information)	• Six color schemes indicating ice thicknesses of: (1) 0 to 0.014-grey (2) lower ice detection limit of the system (or 0.015) to 0.049-green, (3) 0.050 to 0.059-yellow, (4) 0.060 to 0.069-red, (5) 0.070 to 0.249-blue, and (6) 0.250 in and above-magenta • Spot numerical ice thickness readouts within imaging area • Numerical ice thickness displays over selected region to three significant places to the right of the decimal place (in) • Toggled color video display and ice thickness color coded overlay on gray scale infrared image • Out of range flashing white overlay • Indications of system readiness or failure through self-test • Displays for the operator should include: (1) camera images (visual and IR) with ice thickness color indications, (2) numerical values of ice thickness, (3) scale, (4) time, (5) switch information, (6) system readiness or failure, and (7) distance
C-2	A full range of control functions	• Purge on/off valve • Power on/off switch (providing system readiness) • Strobe on/off switch • Density compensation switch (high, medium and low) • Record on/off switch
C-3	Toggle-able angle compensation	• Capability to switch between RSS viewing of 90 degrees to normal (90-95% of the time), and a toggle that will allow 30-50 degree viewing from the MLP
D-1	Automatic angle compensation	• Indication of horizontal inclination and adjustment of thickness values automatically
D-2	Frost detection/ compensation	• Fundamental understanding through R&D of frost thickness determination/compensation to determine underlying ice thickness

Appendix 14: Project Team Lessons Learned and Some Open Issues

Lessons Learned

The following is a listing of project management lessons learned over the 2004-2007 period of MDA ice detection and measurement system development. They are offered to help guide others who may find value in this approach and process. Captured lessons learned by category are as follows:

Agreements:

- It is important to kick off any interagency effort with top level approval and agreement as was done with the joint NASA-KSC/TARDEC Space Act Agreement signed in 2004.
- A more specific Statement of Work (or equivalent) agreement should be signed by working level representatives of each top level agreement signatory for one or more specific and significant problems that have been identified for resolution.
- Each participating organization needs to recognize that there is value in leveraging previous government and commercial organization funded science and technology investments.
- The problem(s) to be solved need to have organization importance.
- Each participating organization needs to be proactive and willing to add significant value to development and testing process.
- Organizational responsibilities need to be understood and agreed to.
- Funding and contracting responsibilities need to be defined early.
- Agreements must transcend organizational "serfdoms" (known in the military as stovepipes").
- All activities should be viewed as part of the projects with performance, schedule, and cost measures considered.

Communications:

- Begin team building with face-to-face meetings to develop trust and understanding.
- Conduct regular (weekly) teleconferences.
- There needs to be a single person responsible for teleconference facilitation.
- Use e-mails between teleconferences.
- Action items should be identified and tracked.
- Provide status (feedback) to management at each stage of development activities.
- Operations personnel must take a direct and active role in the development, testing, and reviews to the developing system, thereby maximizing their future operational effectiveness.
- It is important to work as a team during all phases of discussion, action item identification, tracking, and resolution.

Organization:

- It is important to build win-win, collaborative partnerships (internal and external) and contractor relationships.
- Customers and all stakeholders need to be part of all team project management activities.
- An individual or organization must be identified and serve to orchestrate the total process to ensure that all phases of activities are integrated, continuous, and complete.

- The team must function to improve relevancy and responsiveness to customer/stakeholder needs and requirements and funding agency accountability.
- To shrink time during the project it is important to do parallel and concurrent system development with the following project customers and stakeholder: operational users, designers, engineers, testers, maintainers, management, and funding officials. Involvement of all those concerned in the total process provides value for all those who might only have "paper" access to future prototypes and systems. Serial and "throw it over the wall" project development only extends overall time to completion and communication breakdowns.
- System issues should be identified and resolved early to cut development times.

Problem solving:

- Initially think top level downward from needs/requirements and needs to system design, and upward for solution accomplishment and status reporting.
- Identify points of contact and responsibilities at all levels of development activities.
- Decisions and team consensus needs to be made quickly because of funding constraints.

Some Open Issues

The following are open technical issues to be resolved for the next phases of prototype and operational system development and testing. The letter (P) at the end of an issue indicates prototype applicability, and an (O) means operational system applicability. The following are needed:

Test equipment:

- An improved method of fabricating thin milled SOFI for testing is needed either through better milling machine techniques or by cutting SOFI using a "hot wire." (P) (O)
- Build an enclosure and better environment for ice creation and test setup. (P) (O)
- Investigate a better means of mapping ice surfaces. (P) (O)
- Improved shipping containers should be developed to minimize shipping damage. (P) (O)

Test procedures:

- New procedures are needed to test for the ice camera's capability to determine thick and thin shell ice and frost thickness determination. (P) (O)
- Investigate frost equilibrium thickness vs. the test environment. (P) (O)
- Uniform ice creation is needed to eliminate density variations as a function of time. (P) (O)
- Automate Kaman data acquisition. (P) (O)

Testing methods:

- Efforts should be made to quantify, document Kaman error sources. (P)
- Better methods of frost measurement are needed. (P)
- Find a method to model/measure ice dielectric properties. (P) (O)
- Find a method for anti-convection and diffusion of ice panel cold air. (P) (O)

Appendix 15: Abbreviations

BRDF	Bidirectional Reflectance Distribution Function
BX250	A commercially-available insulation foam sheet
CTC	Cryogen test container
DVR	Digital video recorder
EB	External tank to booster fitting
EM	Electromagnetic
ET	External Tank
FCC	Federal Communications Commission
ft.	Feet
FOV	Field of view
HFOV	Horizontal field of view
IFOV	Instantaneous field of view
in.	Inches
IR	Infrared
KSC	Kennedy Space Center, Florida
kW	Kilowatt
lbs.	Pounds
LCC	Launch Commit Criteria
LH2	Liquid Hydrogen
LN2	Liquid Nitrogen
LO2	Liquid Oxygen
MDA	MacDonald, Dettwiler and Associates Ltd.
MLP	Mobile launch platform
MTBF	Mean time between failures
NASA	National Aeronautics and Space Administration
psi	pounds per square inch
RCC	Reinforced Carbon-Carbon
SAA	Space Act Agreement between NASA-KSC and TARDEC
SANGB or Selfridge	Selfridge Air National Guard Base, Harrison Township, Michigan
SOFI	Spray-on Foam Insulation
SOW	Statement of Work
SSME	Space Shuttle Main Engine
STS	Space Transportation System
SWIR	Short wave infrared
TARDEC	Tank-Automotive Research, Development and Engineering Center, U.S. Army
UV	Ultra violet
VCR	Videocassette recorder
VFOF	Vertical Field of View
VGA	Video graphics array
VPL	Visual Perception Laboratory at TARDEC

Appendix 16: References

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10. Nicodemus, F. E., “BRDF,” *Applied Optics*, Vol. 9, No. 6, June 1970.

Appendix 17: STS-118 pictures

Figure 17-1. Inside the Ice/Debris monitor area

Fig 17-2. The ice camera being used by the ice and debris team during the walk-down inspection

Figure 17-3. Unloading of the ice camera on the MLP